Structure and Evolution of Galaxies: Prospects Near and Far

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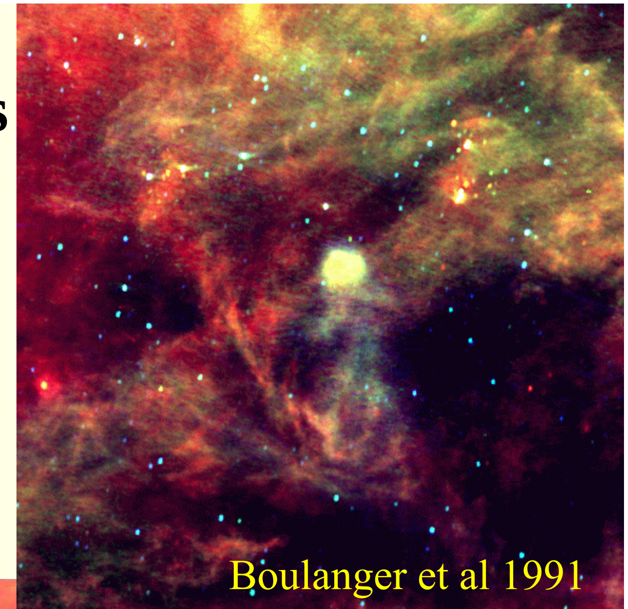
"From Spitzer to Herschel and Beyond:
The Future of Far-Infrared Space Astrophysics"
Pasadena, June 2004

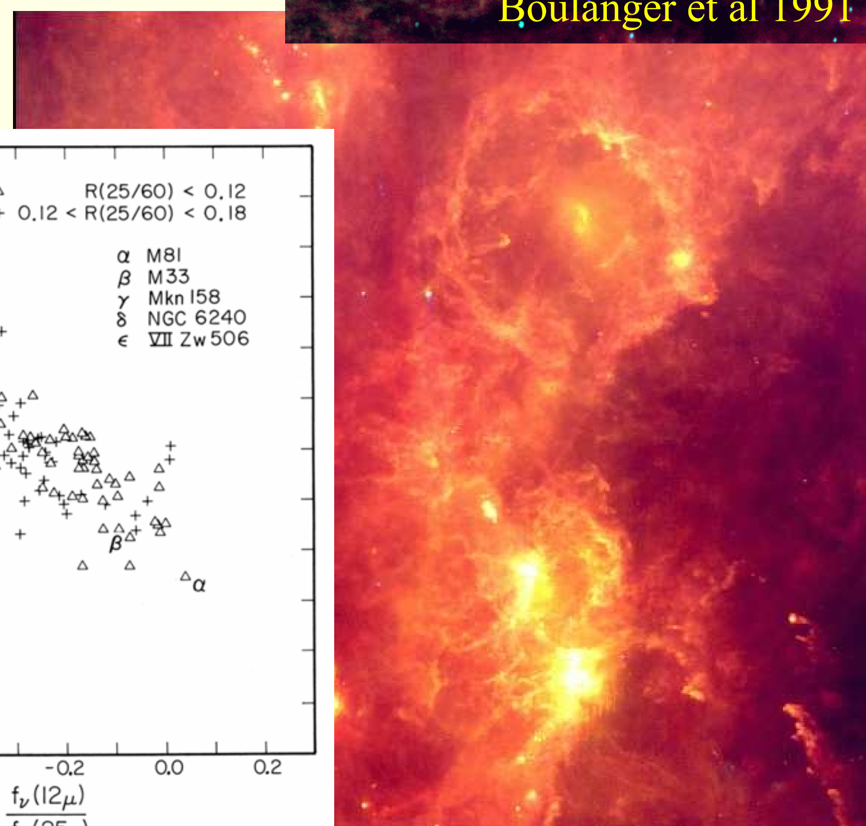
THEMES

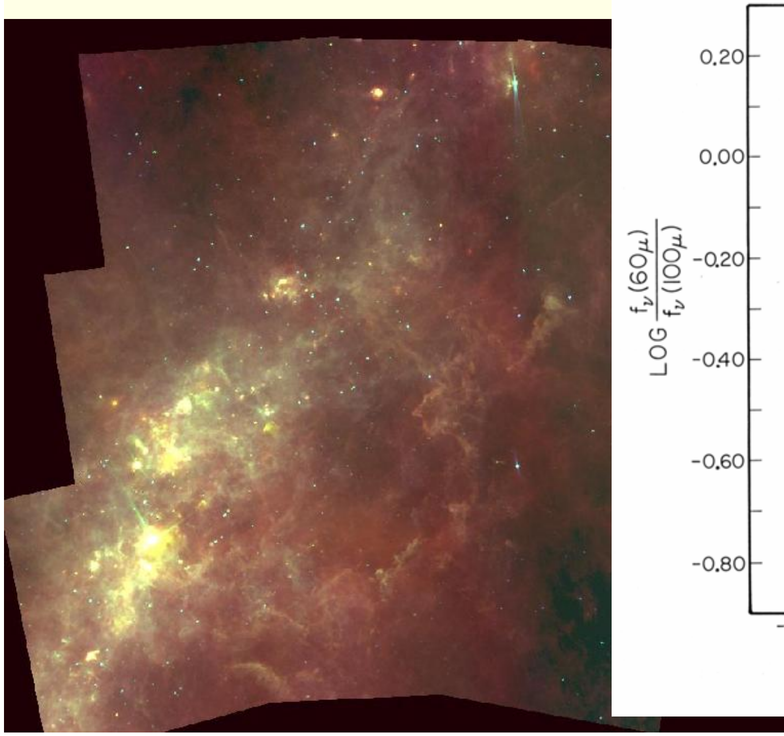
- Measures and mechanics of star formation in nearby galaxies
  - *Structure and evolution of the ISM*
- The IR/Submm energy generation at $z = 0 \sim 2$
  - *Global line emission properties*
- Tools:
  - *Aromatic Features and other continuum signatures*
  - *Mid-IR and Far-IR Fine Structure Lines*

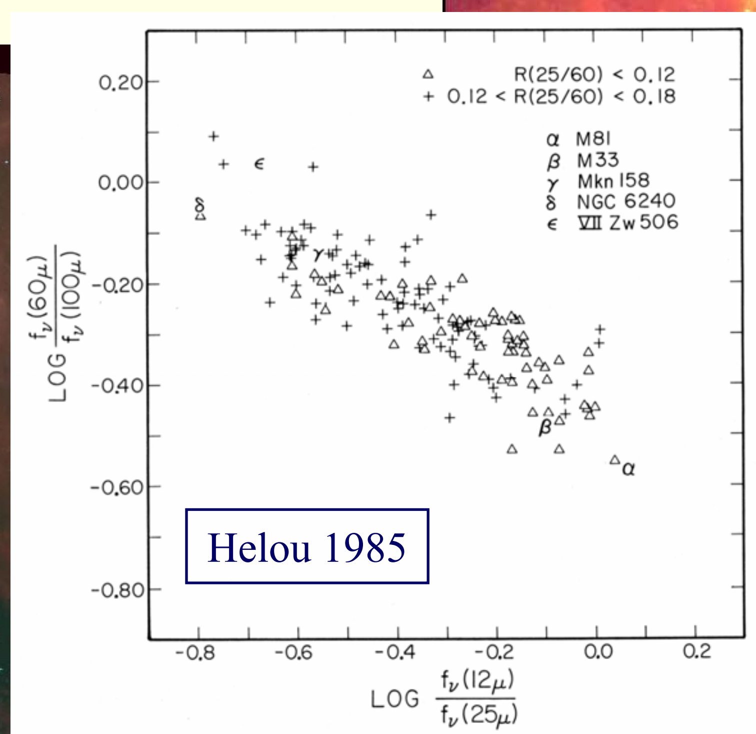
IRAS: First Detections of Aromatic Features

- All-Sky Survey revealed cirrus at all λ
  - *12, 25 μm emission far from stars*
- Colors of galaxies required fluctuating grains as well
- Puget & Leger (1985) proposed Polycyclic Aromatic Hydrocarbons (PAH) as the small fluctuating grains


Boulanger et al 1991



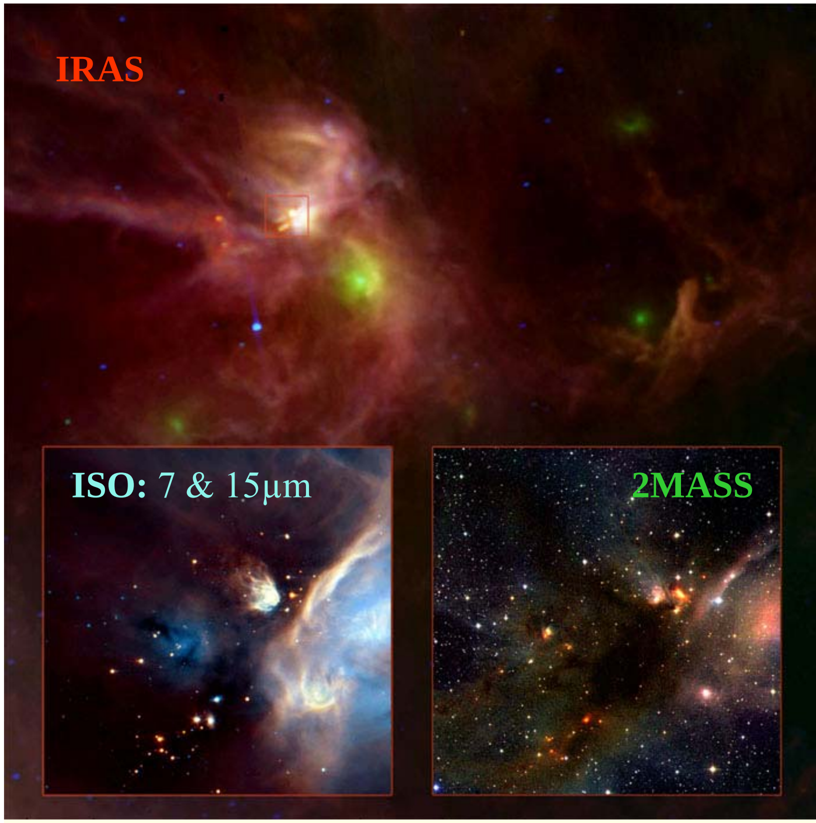


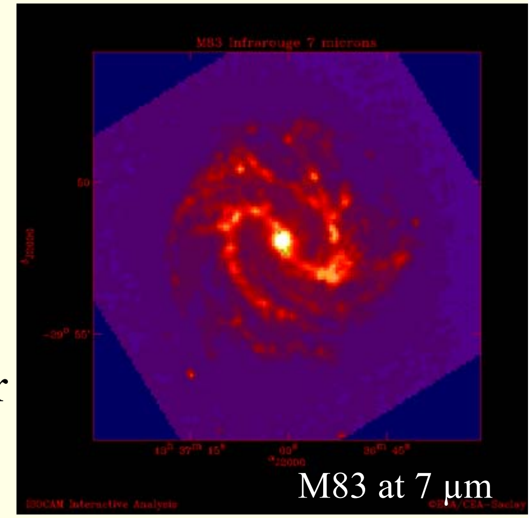


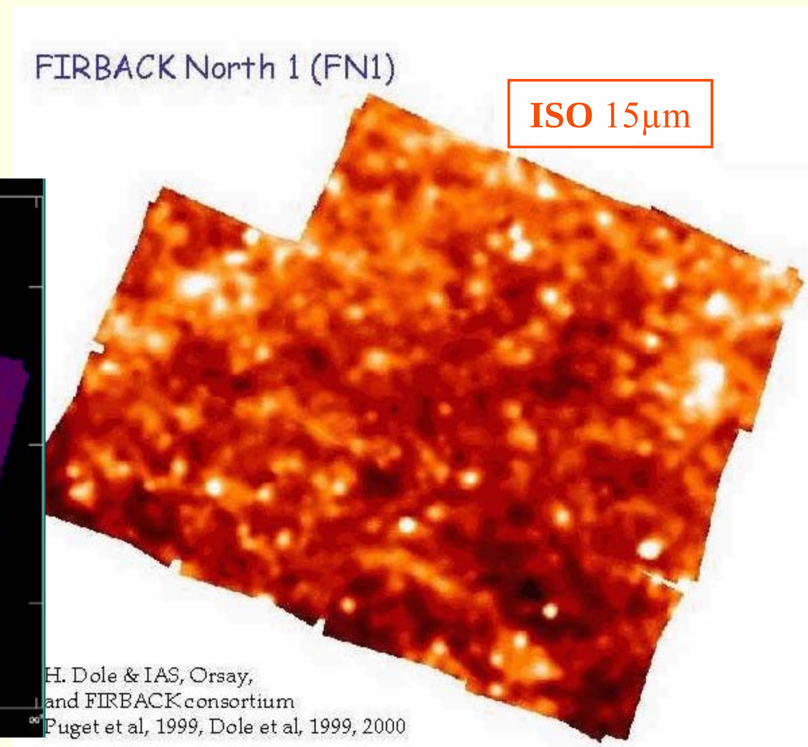
Helou 1985

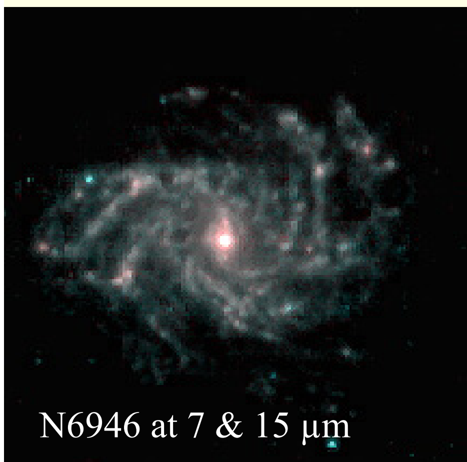
ISO: Details Emerge in Imaging …

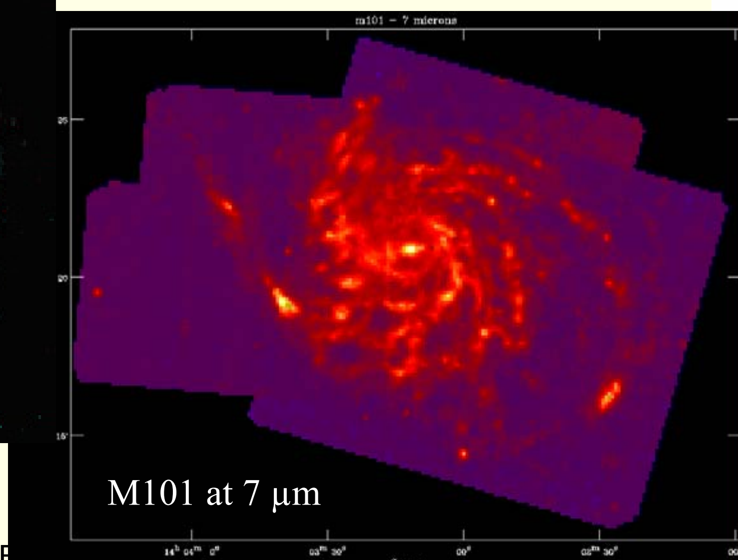
- Mid-IR imaging of Milky Way, nearby galaxies and deep surveys showed mid-Infrared emission as a ubiquitous presence
- Aromatic emission from clouds is skin deep, thinner than attenuation depth of exciting radiation (>6 eV)







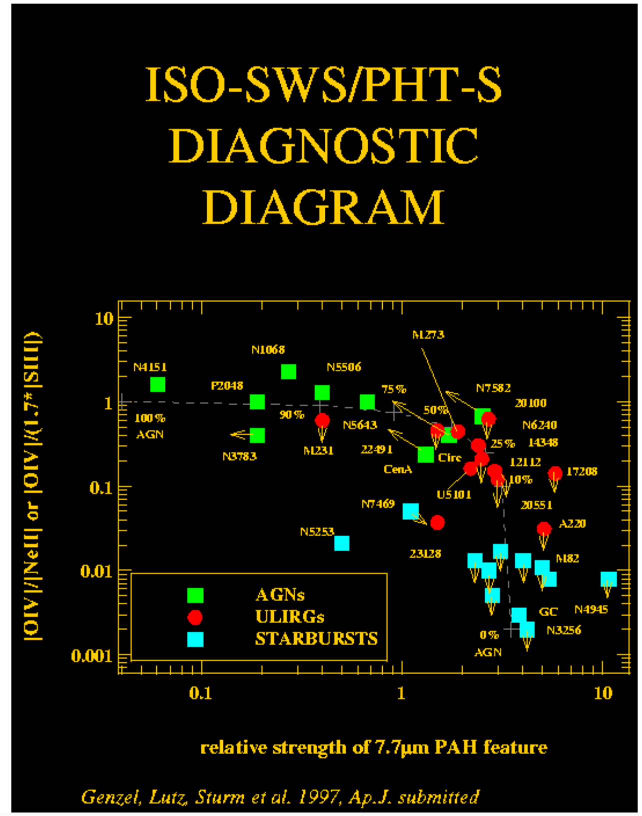


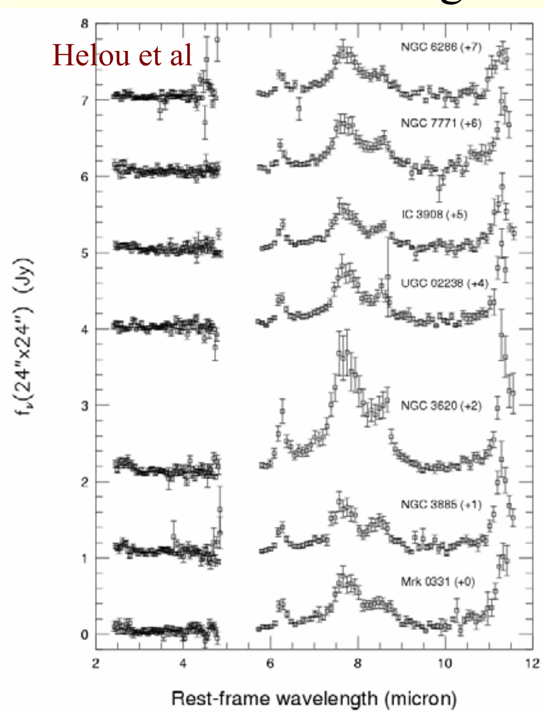


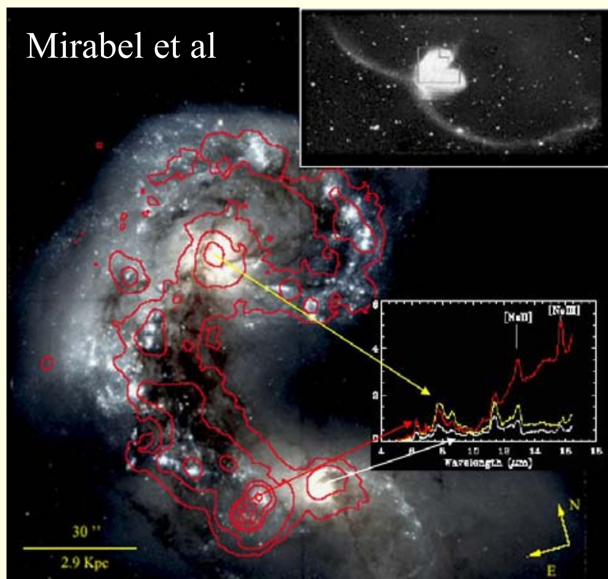
Spitzer, Herschel & E

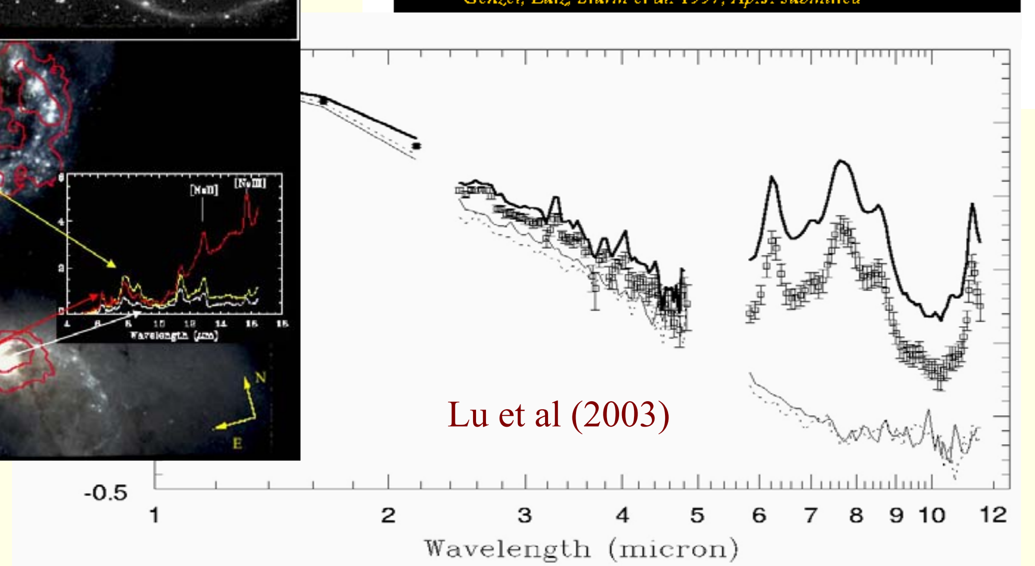
ISO: Breakthrough in Spectroscopy

- Spectral signature of Aromatic Features is invariant over a wide range of conditions
  - *PAH conjecture is still leading, but identification is weak*
- Integrated spectra of star forming galaxies are dominated by Aromatic Features
  - *Destroyed at high UV intensity, e.g. AGN or HII regions*
- Useful parameter in diagnosing power source in IR luminous galaxies



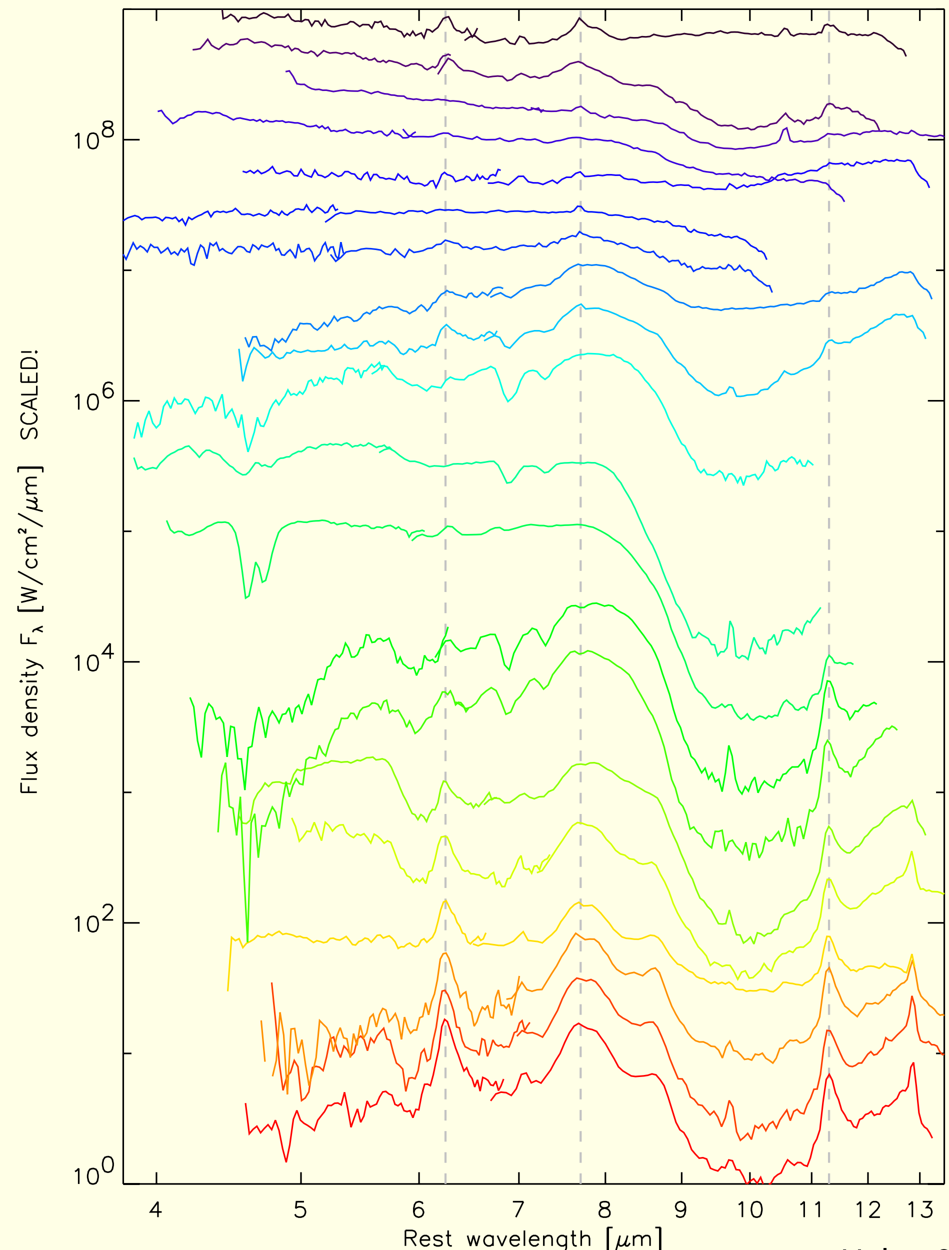






Spitzer Spectroscopy

- See Armus talk from session A

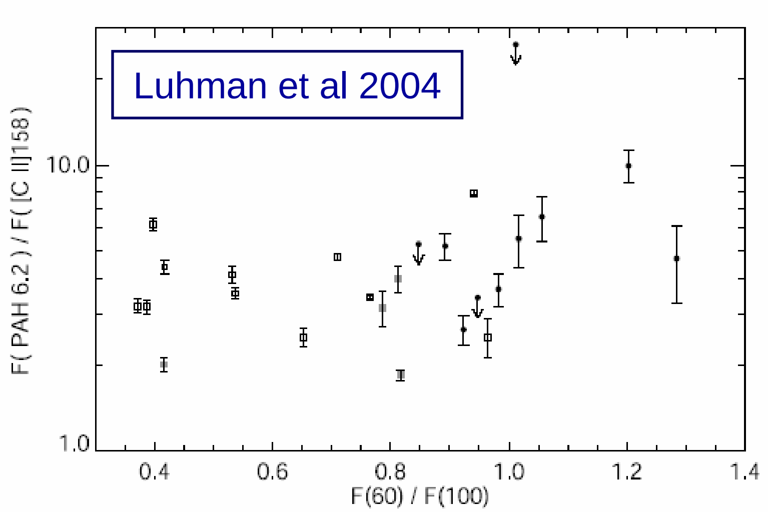


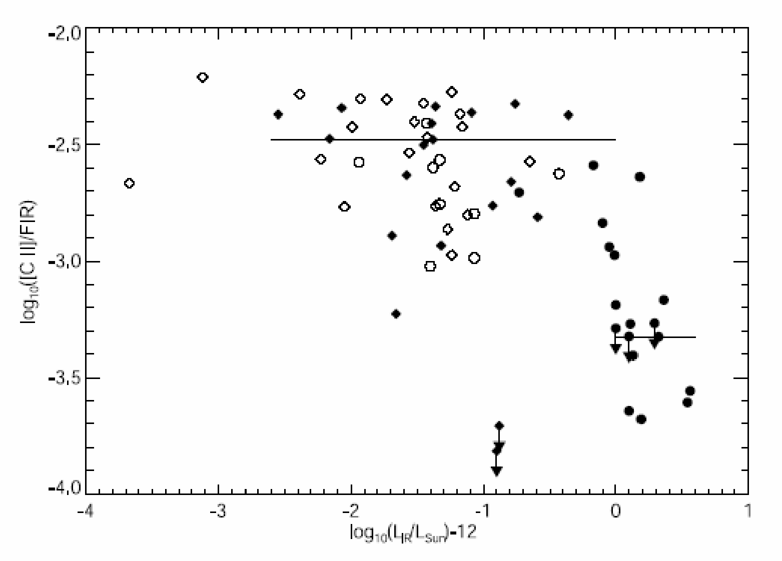
Aromatics: Key Player in the ISM

- Clearly ubiquitous, in MW and among galaxies
- Indirect evidence for their presence at redshifts to z~2.5
  - *24μm counts below 200μJy point to rest-frame emission at ~8μm*
- Prime drivers of photo-electric effect
  - *Smallest grains make greatest contributions*
  - *Key to coupling radiation to gas in non-ionized regions*
- Prime suppliers of electrons to the ISM, even in less ionized regions

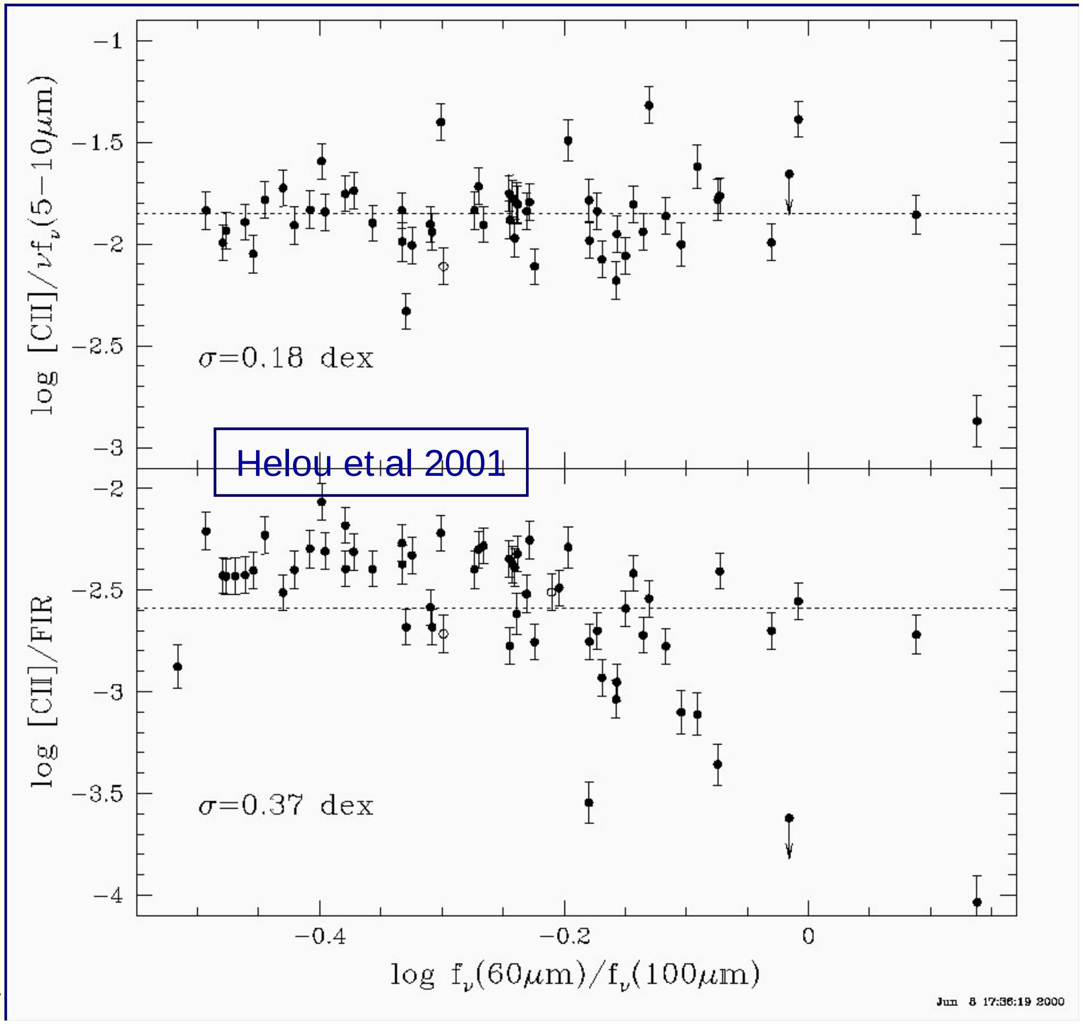
Basic Physical Processes at Work?

- Aromatic Feature Emission (AFE) relation to CII emission
  - *While [CII]/FIR drops as SF activity rises, [CII]/F(AFE) does not!*



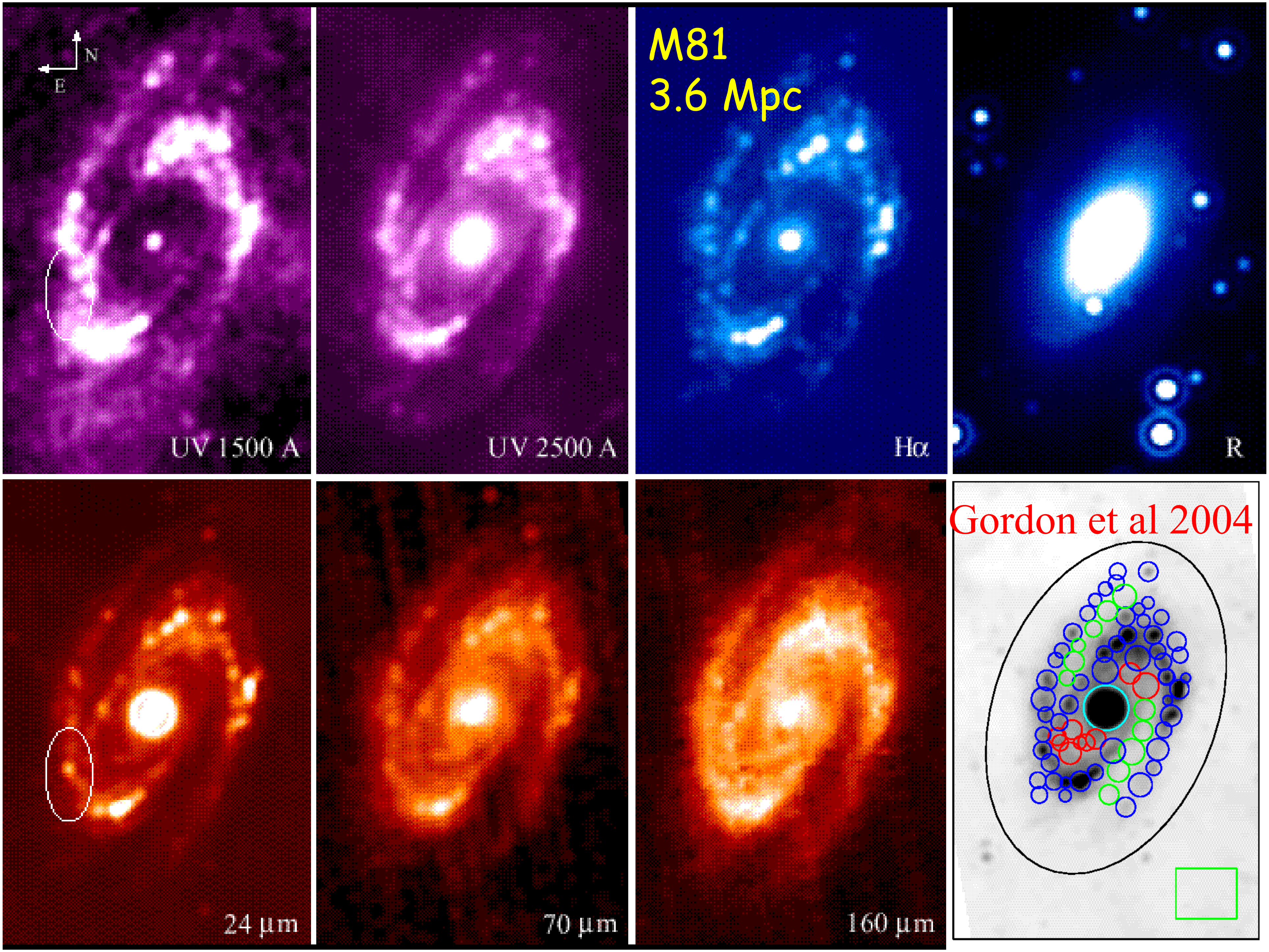


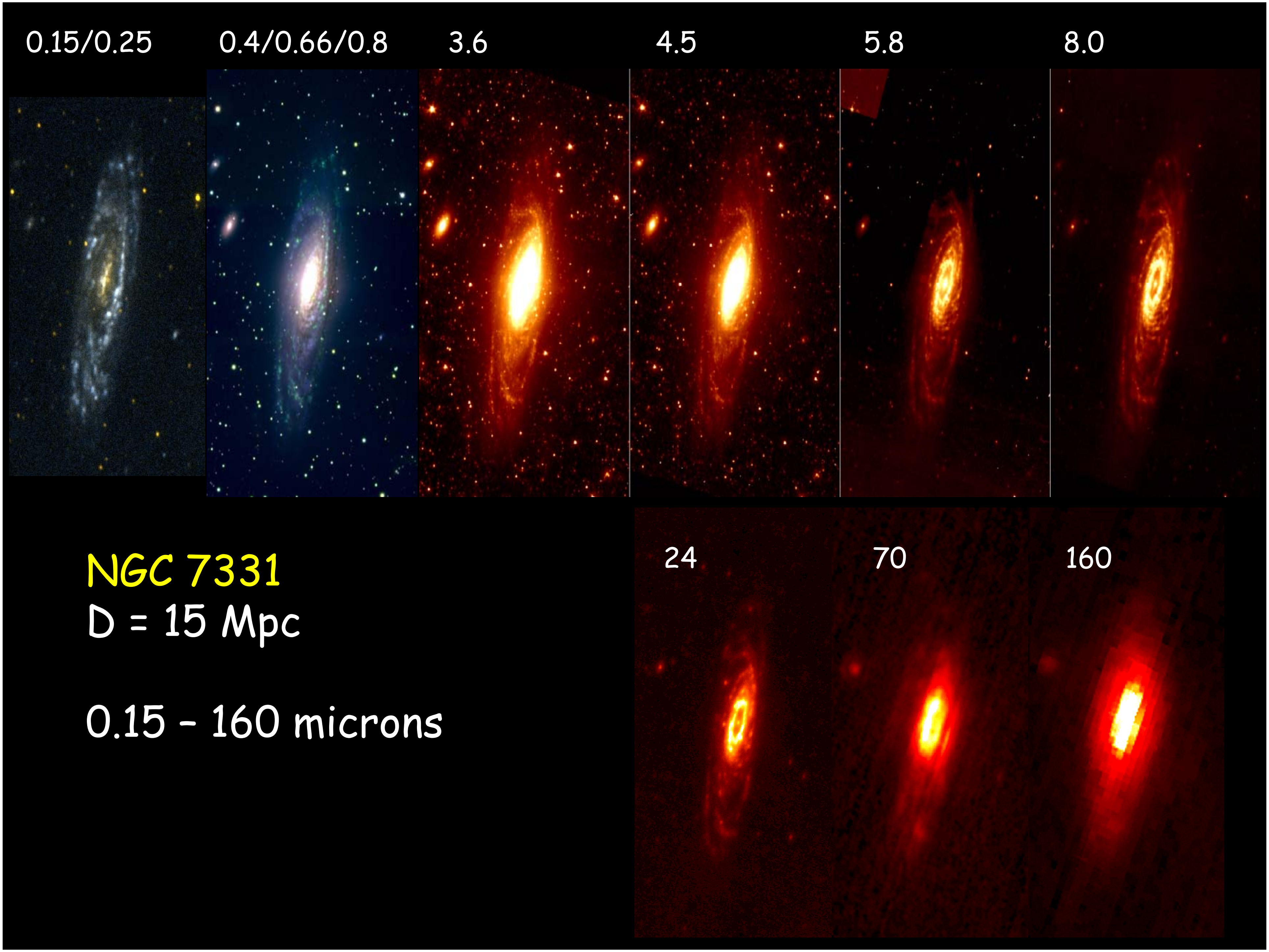
2004

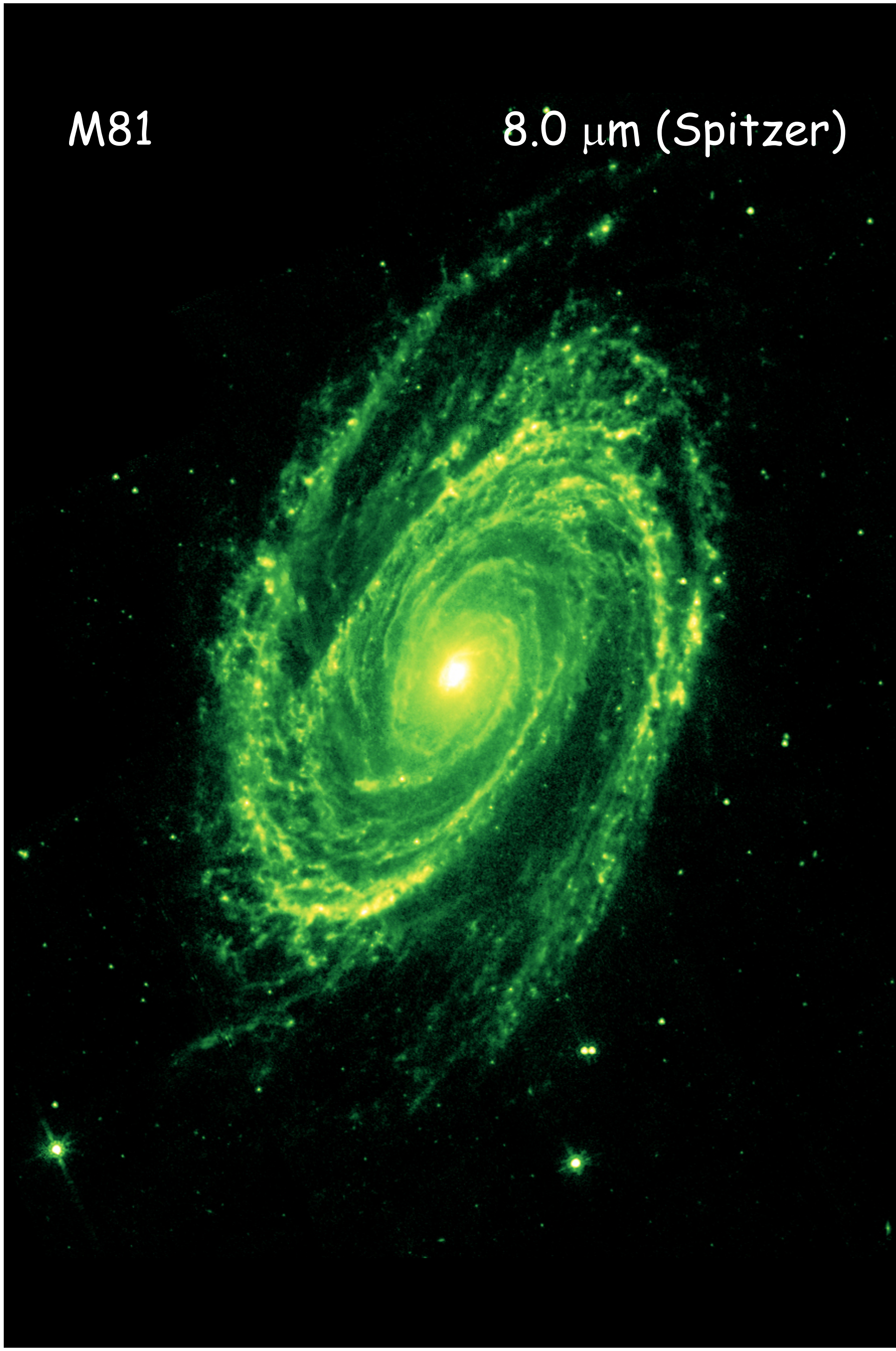


Spitzer Contributions

- Spitzer is dramatically improving knowledge of galaxy SED's and morphologies
  - *Including mid-IR Aromatic Feature range*
- Spitzer is filling-in the picture of mid-IR behavior in the Local Universe
  - *Low-metallicity galaxies, dwarf galaxies, 1Myr old starbursts, etc*


N
E
UV 1500 A
UV 2500 A
M81
3.6 Mpc
Hα
R
24 μm
70 μm
160 μm
Gordon et al 2004


0.15/0.25
0.4/0.66/0.8
3.6
4.5
5.8
8.0
NGC 7331
D = 15 Mpc
0.15 - 160 microns
24
70
160

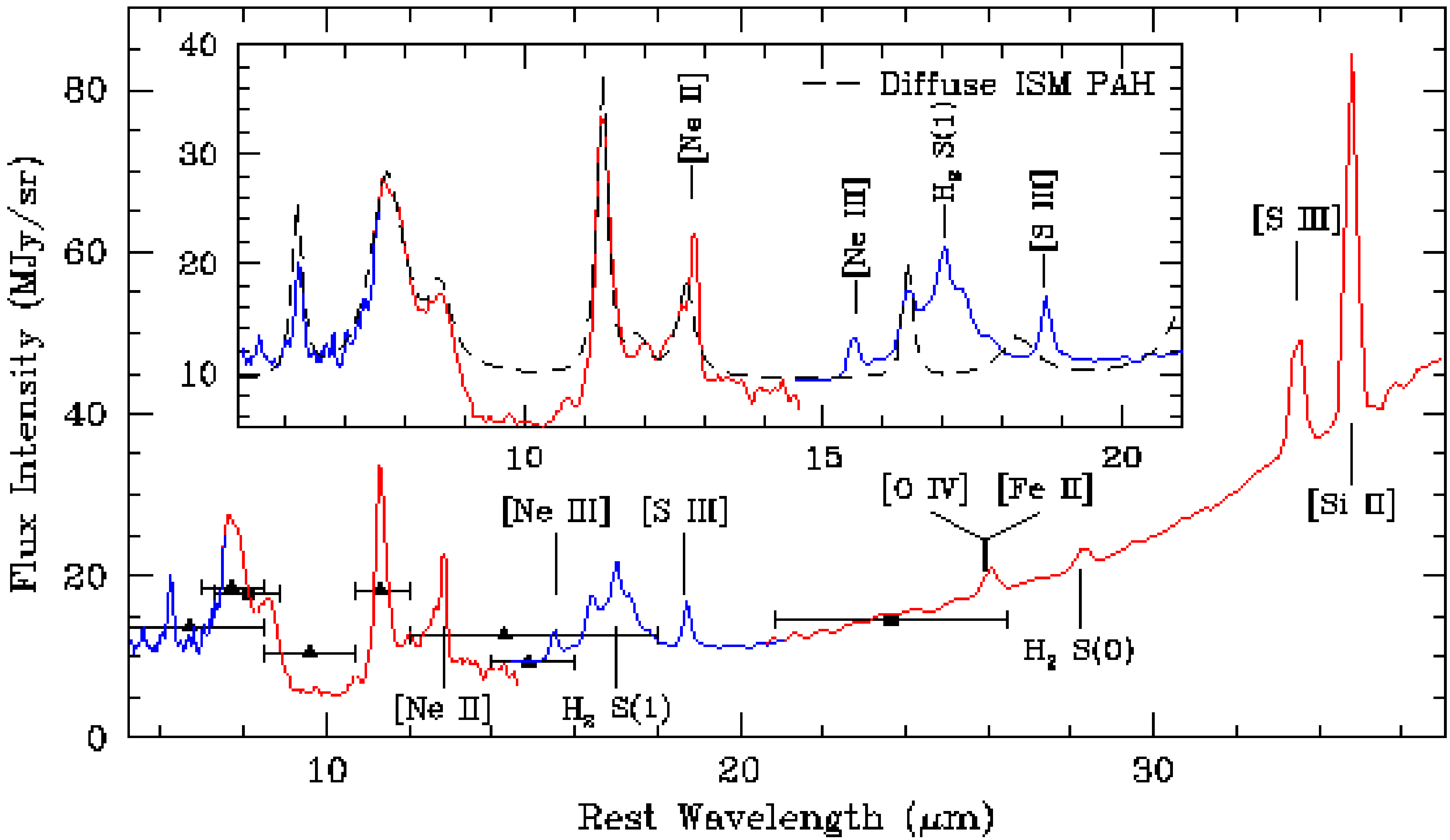

M81
8.0 μm (Spitzer)


UV (GALEX)

N7331

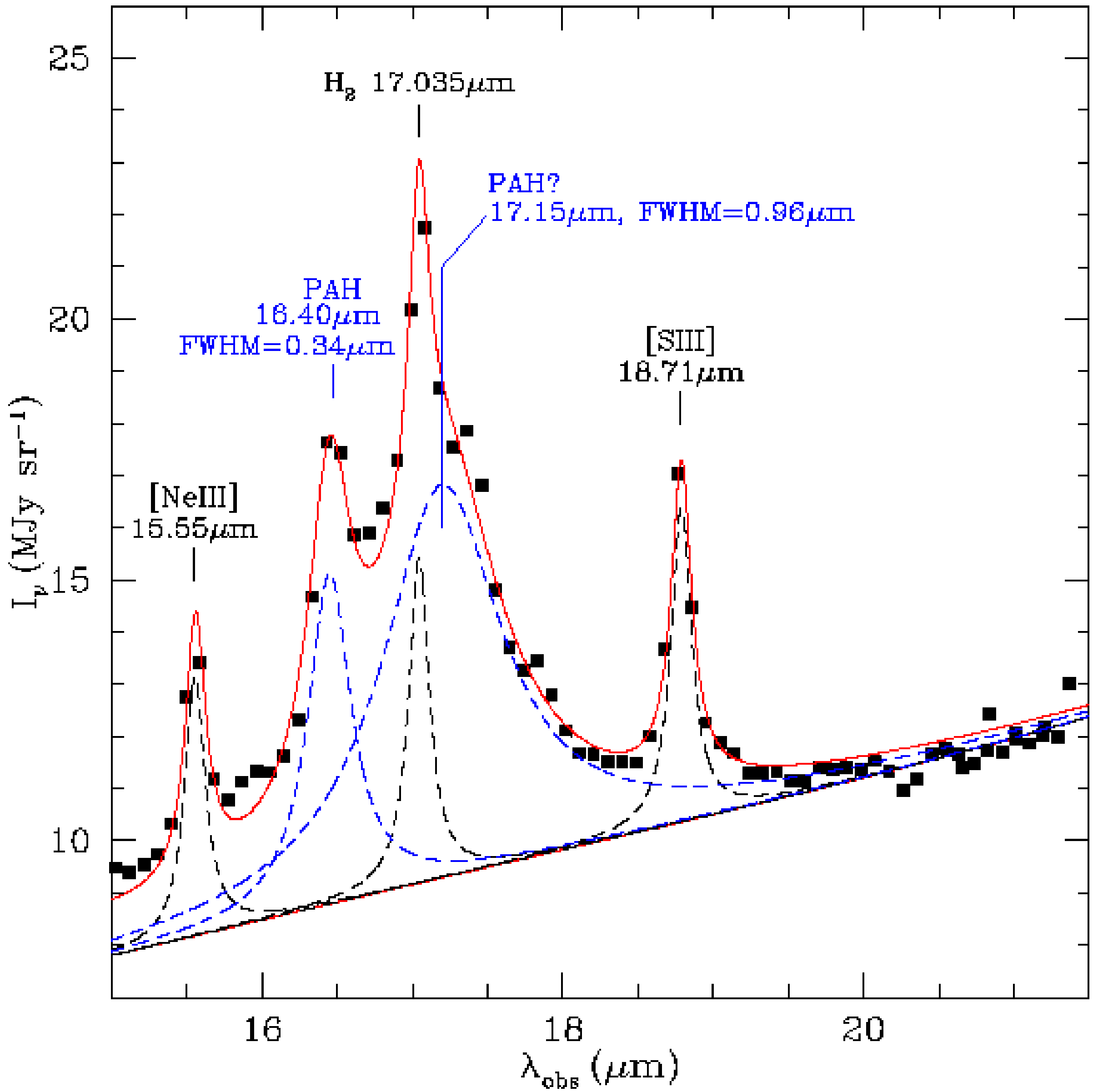
Note bright IR ring is UV-dark

N7331: Low-Res Spectroscopy of nuclear region + bright IR ring



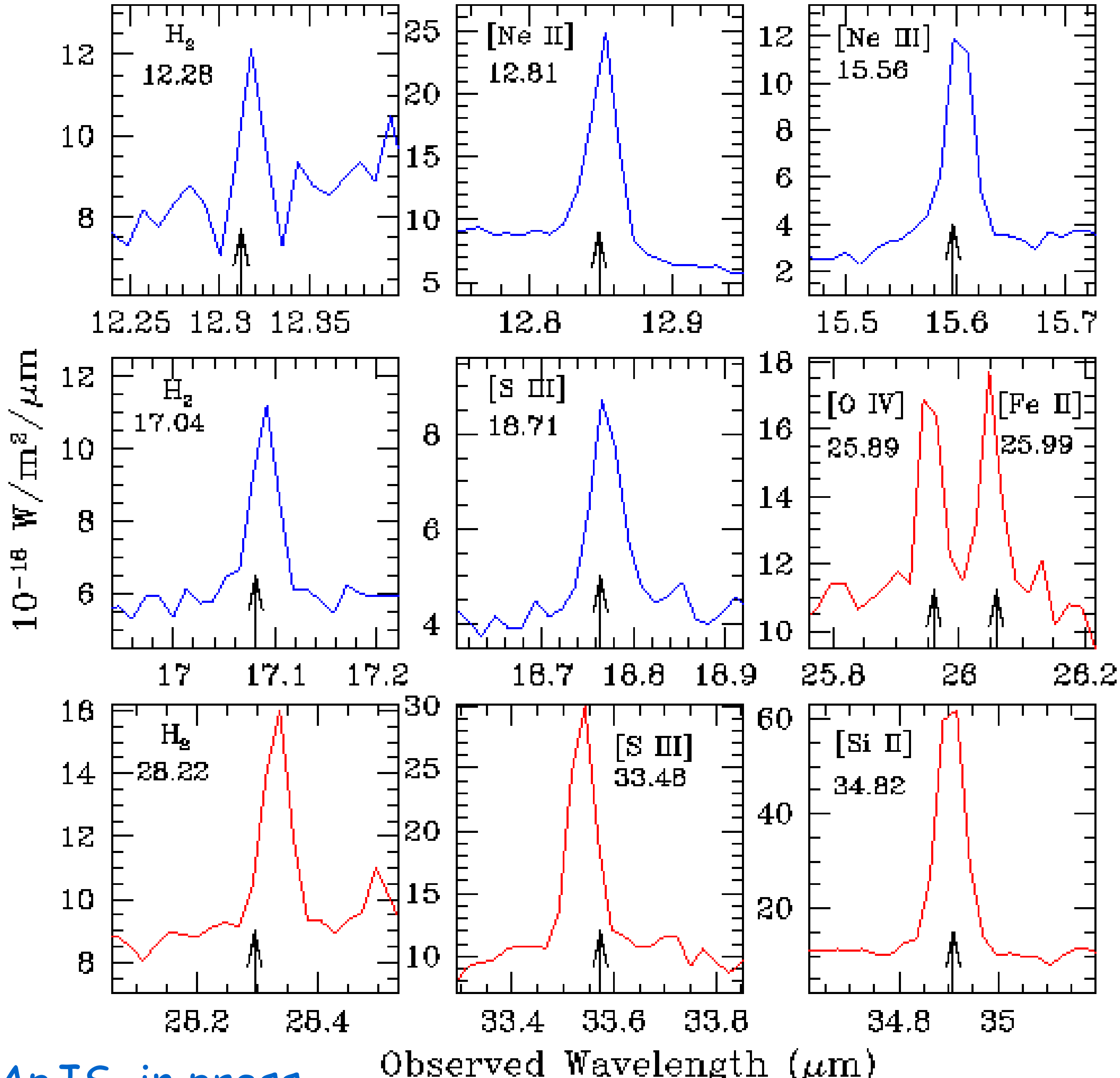
Smith et al. 2004, ApJS, in press

N7331: Detail of the new Aromatic Feature at 17μm



Smith et al. 2004, ApJS, in press

N7331: Hi-Res spectroscopy of nuclear region + bright IR ring

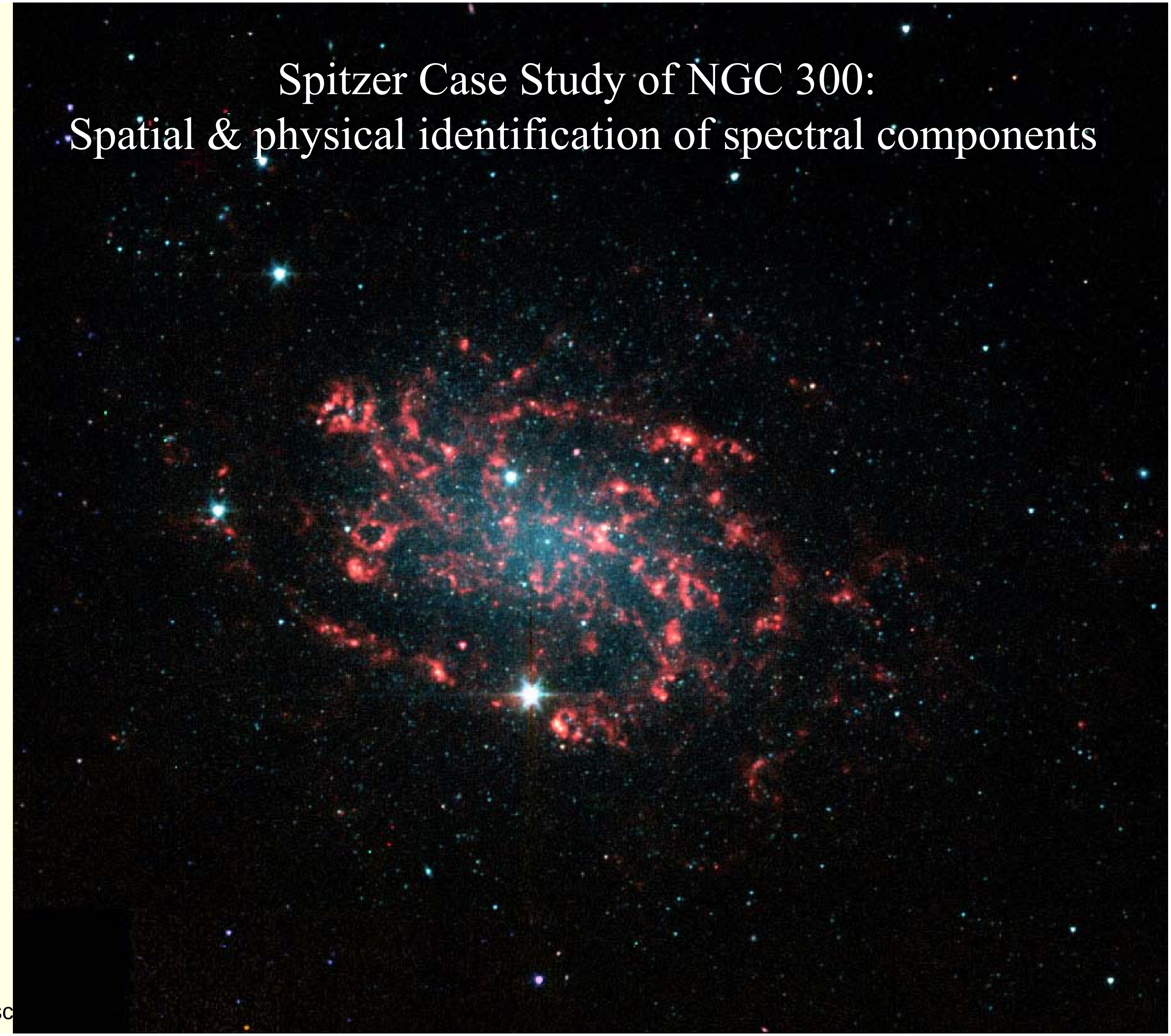


In ring, Si II carries 0.7 to 1% of L(FIR)

Ne II and S III each carry half that fraction

Smith et al. 2004, ApJS, in press

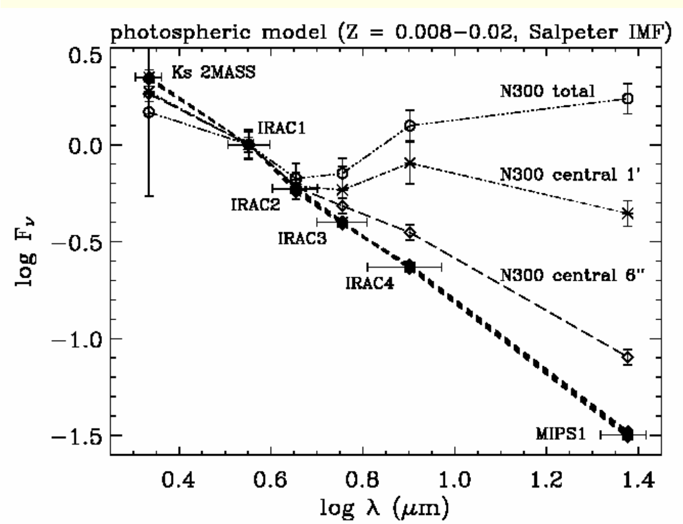
Spitzer Case Study of NGC 300:
Spatial & physical identification of spectral components



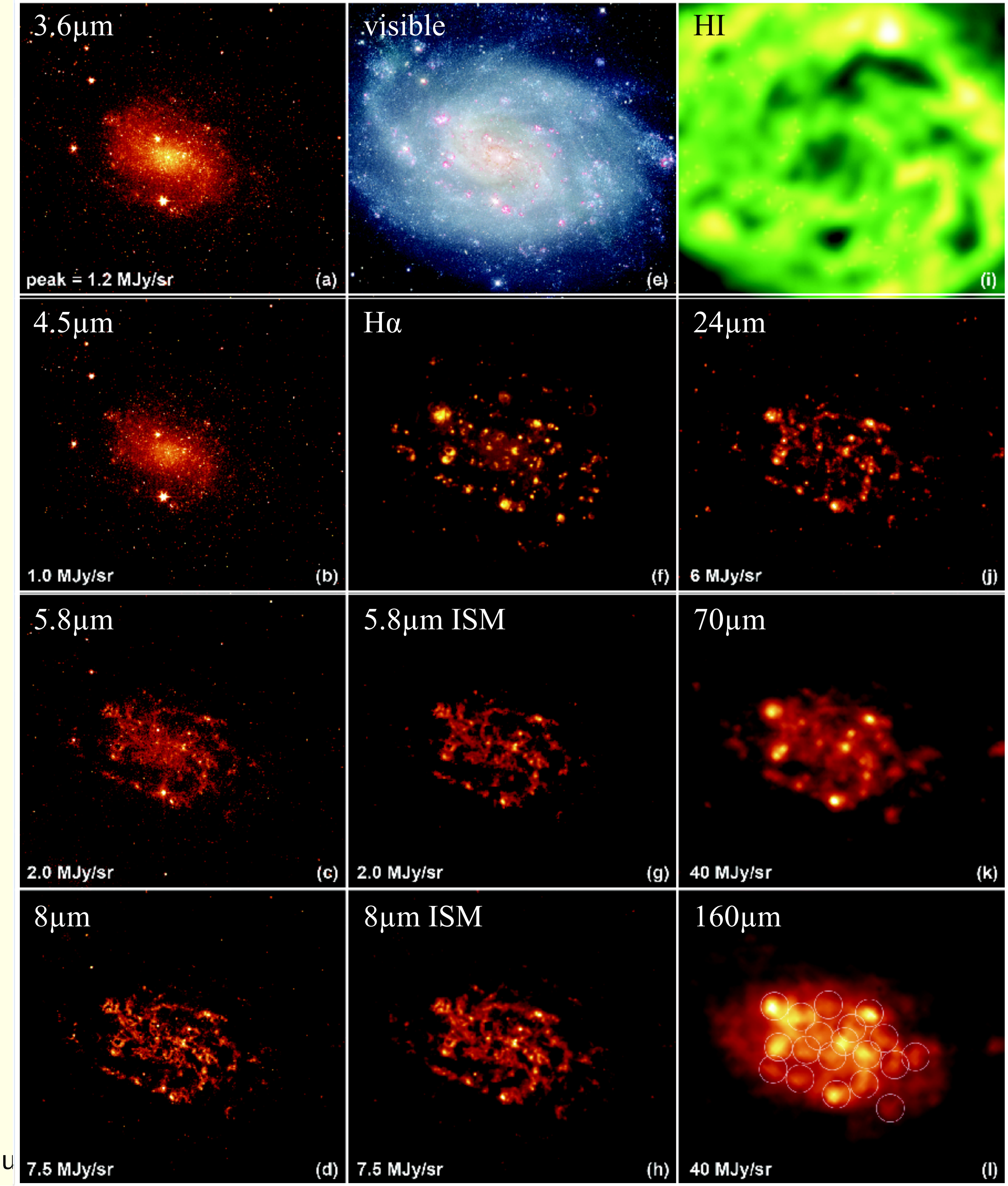
Spitzer, Hersc

NGC 300 Gallery
20′×20′ frames

Star/dust decomposition

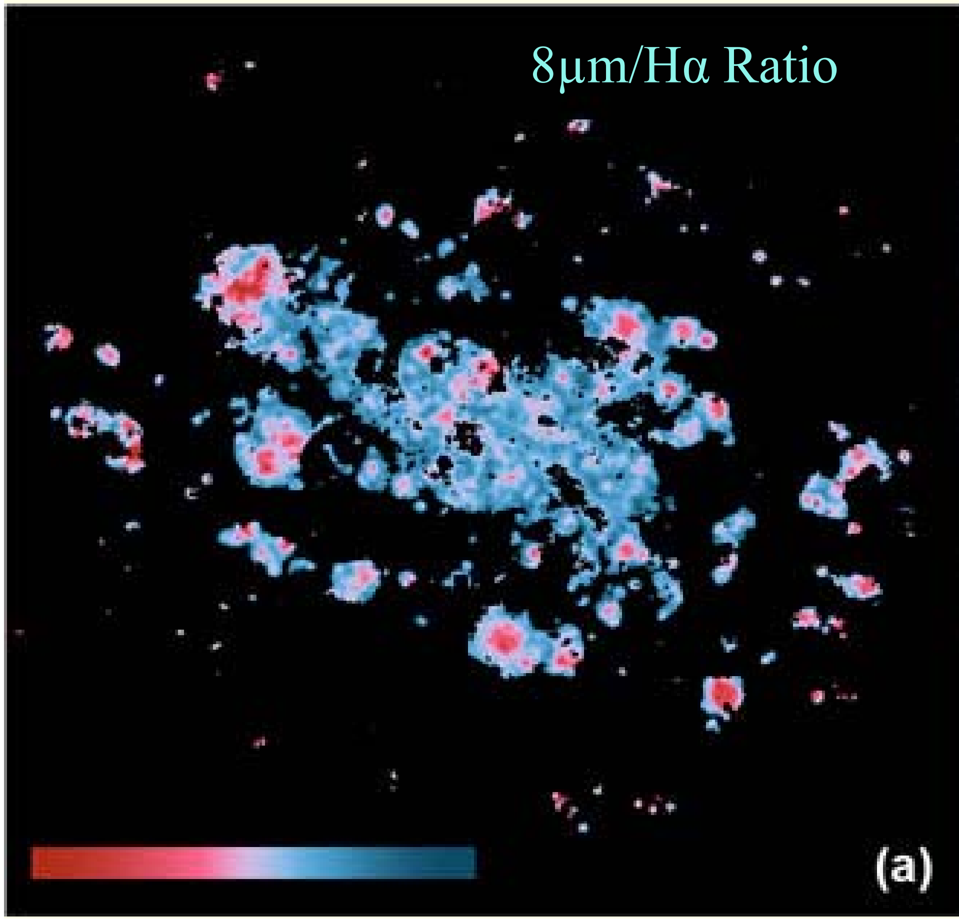


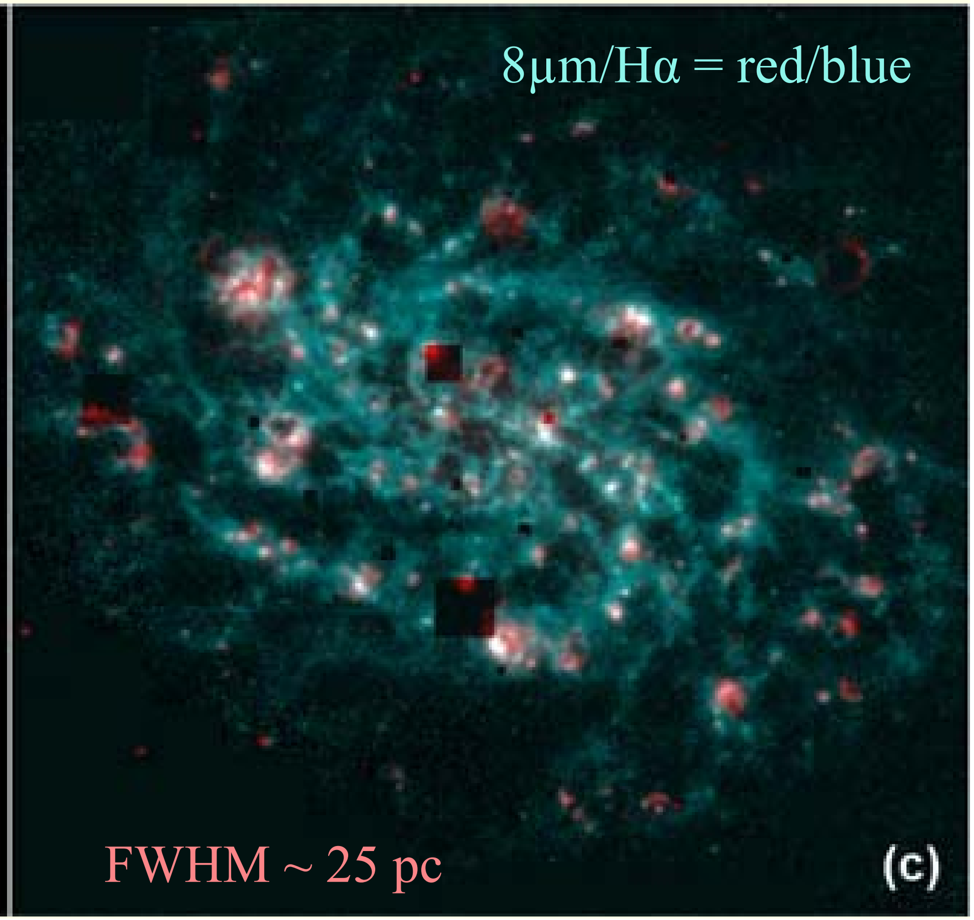
ISM fraction	81%	98%



NGC300: 8μm(dust only)/Hα Ratio Comparison

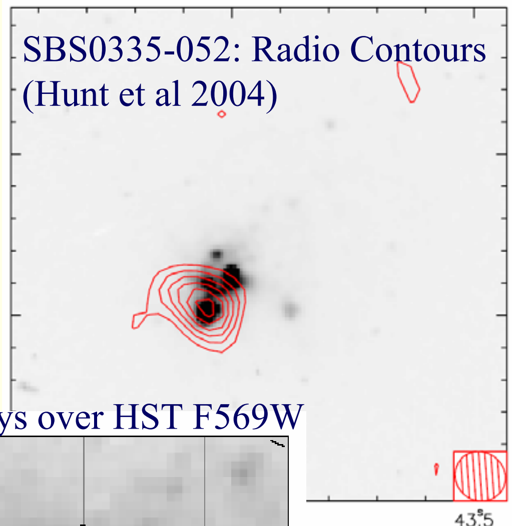
- 8μm PAH emission highlights rims of HII regions
  - *Aromatic Feature Emission traces Photo-Dissociation Regions (PDR)*
- Ratios rise by ×5-10 from inside to just outside HII regions, and maybe more further out
- Averaged over ~1 kpc regions, ratio of 8μm/Hα is consistent with other galaxy disks
  - *Value of 8μm as estimator of massive star formation rate under the right conditions*

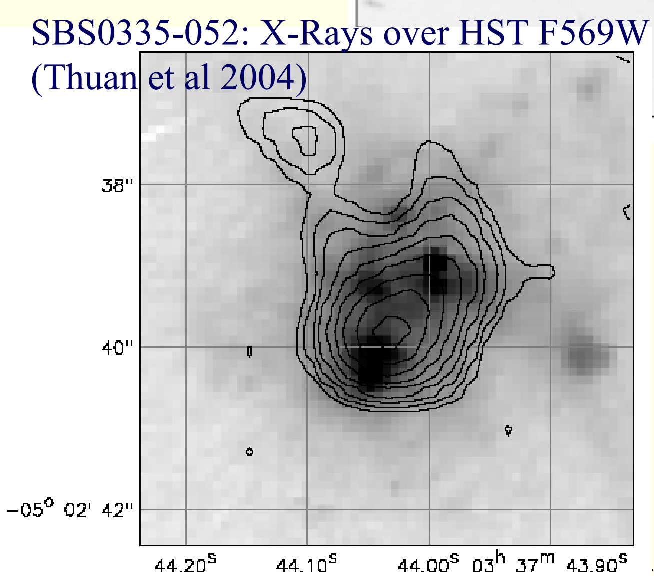




SBS0335-052: Low Metallicity Nearby

- Houck et al (2004) Spitzer data:
  - *No Aromatic Features, no H_2 , and no far-IR emission?*
  - *Is this really a "forming galaxy analog"?*





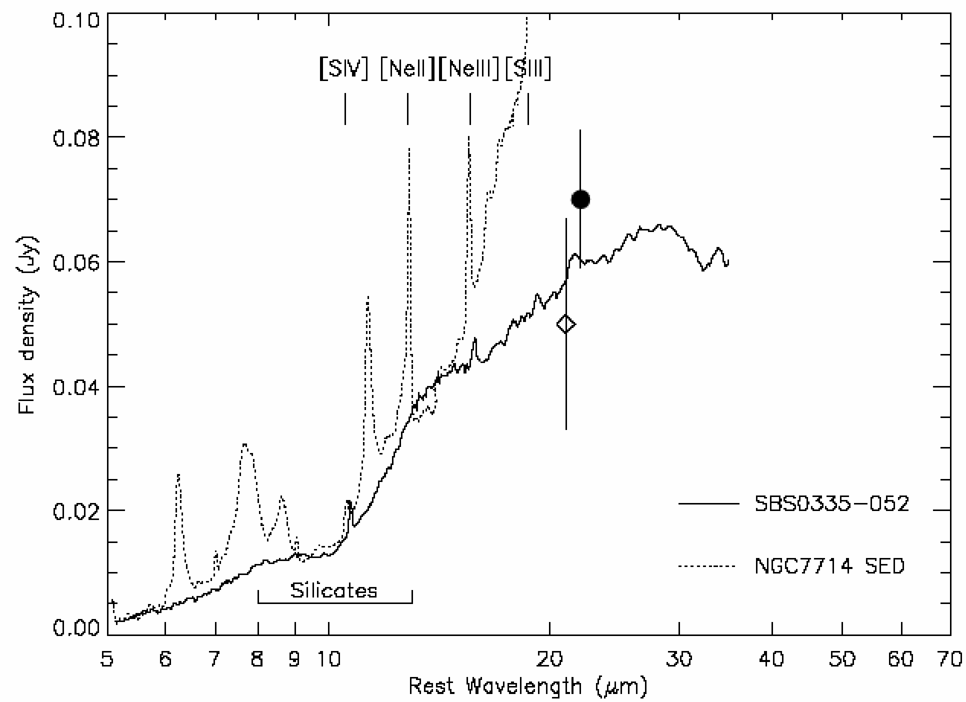


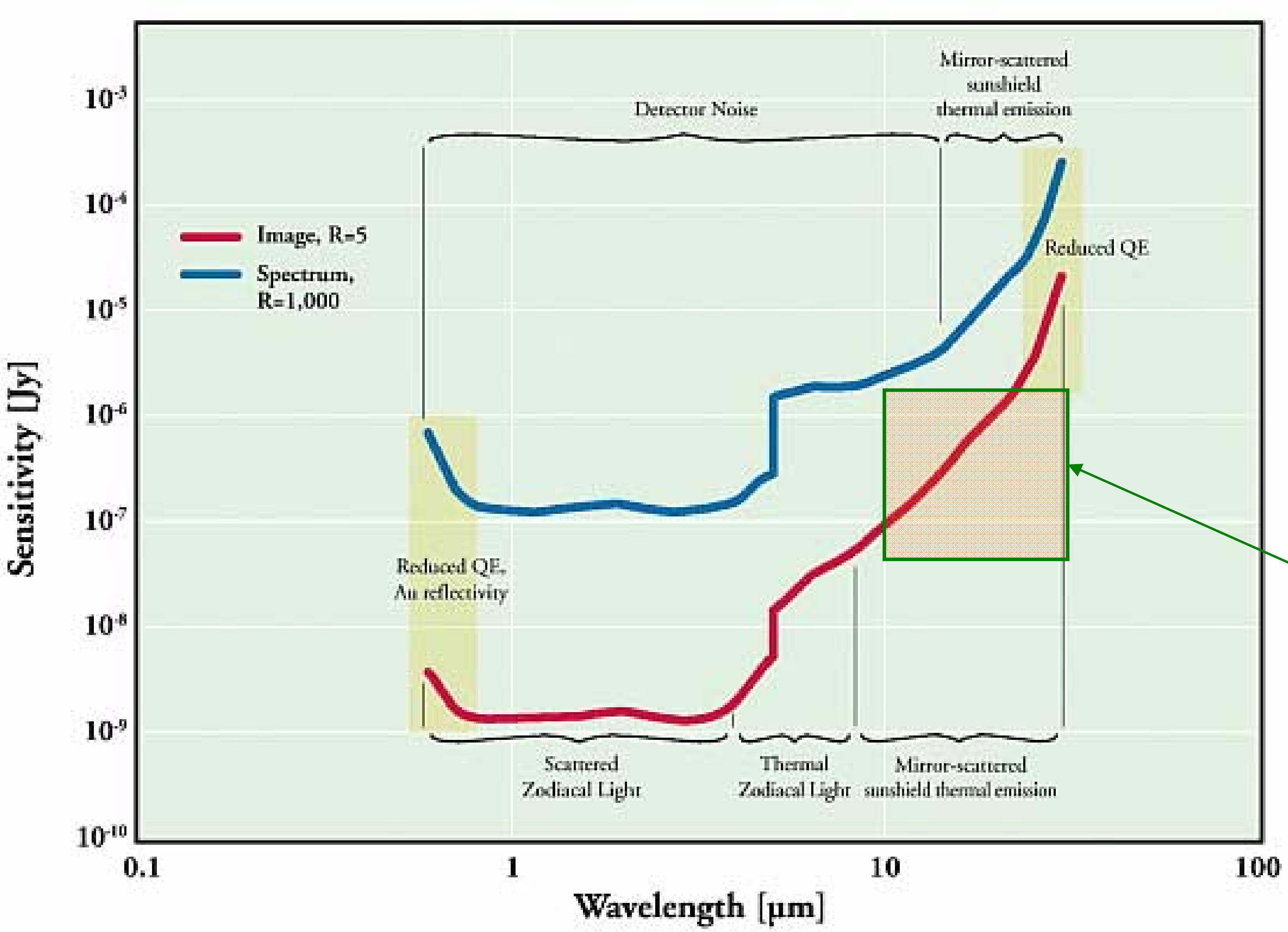
FIG. 1.—The IRS low resolution spectrum of SBS 0335-052 is presented (solid line) along with the spectrum of NGC 7714 (dotted line) from Brandl et al. (2004). The spectrum of NGC 7714 has been divided by 9.53 so that its 14 μm flux density matches that of SBS 0335-052. Note the complete lack of PAHs in the spectrum of SBS 0335-052 as well as the spectrum peak at ∼30 μm (see Section 3.1). The solid circle is our 22 μm peak-up photometric point, while the diamond corresponds to the 21 μm Gemini point from Plante & Sauvage (2002).

Prospects

- What is relation of Aromatic Features to far-IR dust as a function of z=0-2.5?
  - *What is role of Aromatic Feature carriers in formation and evolution of dust?*
- How does metallicity affect the mid-IR spectrum of galaxies?
- Are the Starburst/AGN components truly separable in the mid-IR spectrum?

- Can we trace the rise of dust (and therefore of metals) at 2<z<3 or 4?
  - *Spitzer will address in Local Universe*
    - L* ~10^{10} L(sun) galaxies can be studied well to z=0.1
    - Luminous galaxies ~10^{12} L(sun) can be studied to z=0.6
  - *JWST is borderline for L* galaxies at z=1 (30 hour integration)*
  - *L* at z=2 requires cooled 10-meter aperture*

Prospects-2



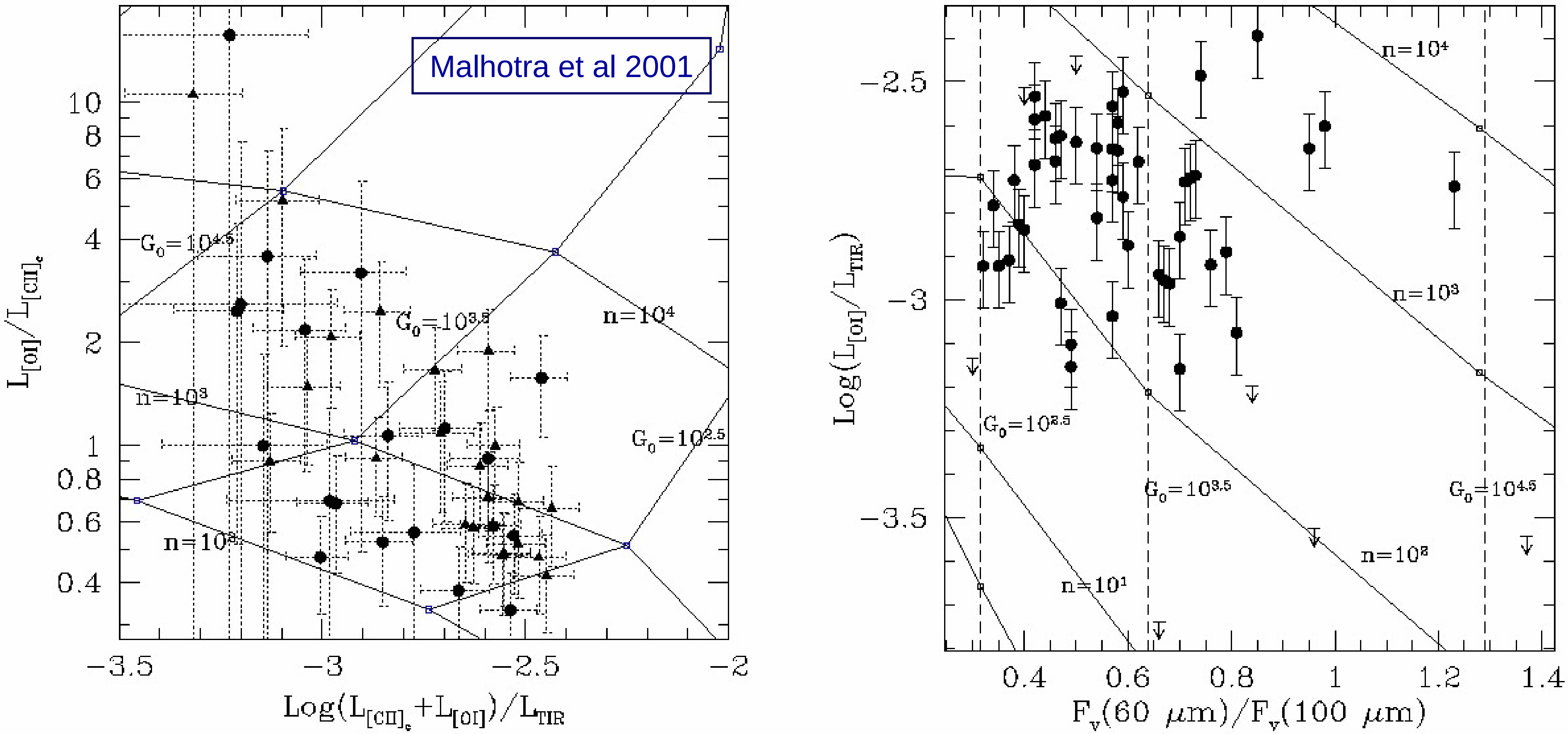
Target zone for Aromatics in L* galaxies at z=1-2

Far-IR Fine Structure Lines

- First measured by Harwit et al from airplanes and sounding rockets
- ISO-LWS made it possible to study "normal galaxies" whereas KAO had only studied starbursts
- Dominant coolers of neutral ISM: [CII] 158μm, [OI] 63μm, L>>1000 L(CO)
  - *Similarly, NII, OII, NIII, OIII lines important for HII regions*
- [CII] cools the CNM: C^+ is abundant (IP=11.26 eV), and 158μm is easy to excite ($\Delta E/k \sim 90K$)
- At $T \geq 200K$, $n \geq 6\ 10^5\ cm^{-3}$, [OI] takes over; [OI] 63μm requires $\Delta E/k \sim 224K$.
- Most [CII] flux from galaxies is thought to originate in Photo-Dissociation Regions (PDR), interfaces between HII regions and molecular clouds.
  - *Additional [CII] is contributed by the diffuse neutral medium.*
- In PDRs, both [CII] 158μm and [OI] 63μm transitions are collisionally excited by photo-electrons extracted from dust by UV photons.
  - *Photo-electric yield $\leq 10^{-2}$ varies weakly for ISM illuminated by starlight.*

FIR Fine-Structure Lines as ISM Diagnostics

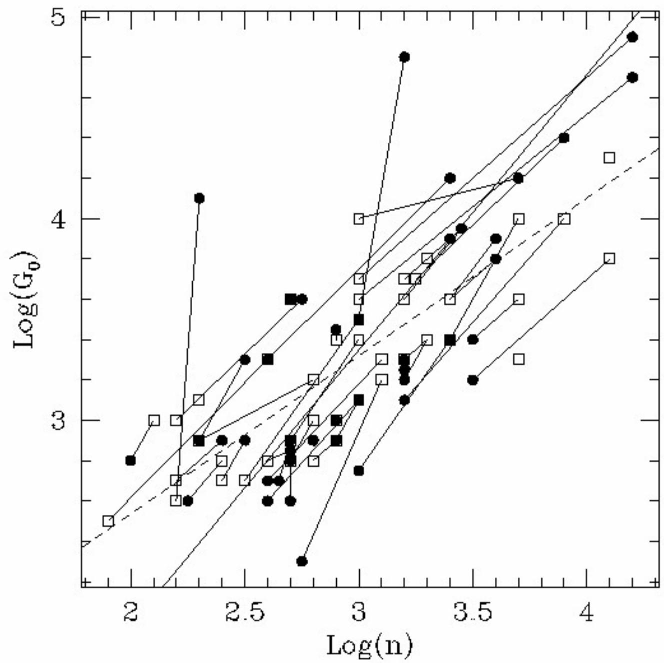
- Traditionally, IR fine-structure line studies in the Milky Way have relied on PDR modeling to deduce physical parameters (n, U, T) of PDR from data. See Hollenbach & Tielens (ARA&A 1997).
  - *Complications include CII emission from HII regions, OI optical depth*



Scaling Relations from Model Derived Parameters

- Tempting to interpret such a relation as a "Schmidt's law" for star formation
- However, this is more likely a result of "Strömgren sphere" scaling relations, reflecting density variations within the natal clouds of massive stars

- High-resolution data from Spitzer (mid-IR), SOFIA and Herschel will address directly

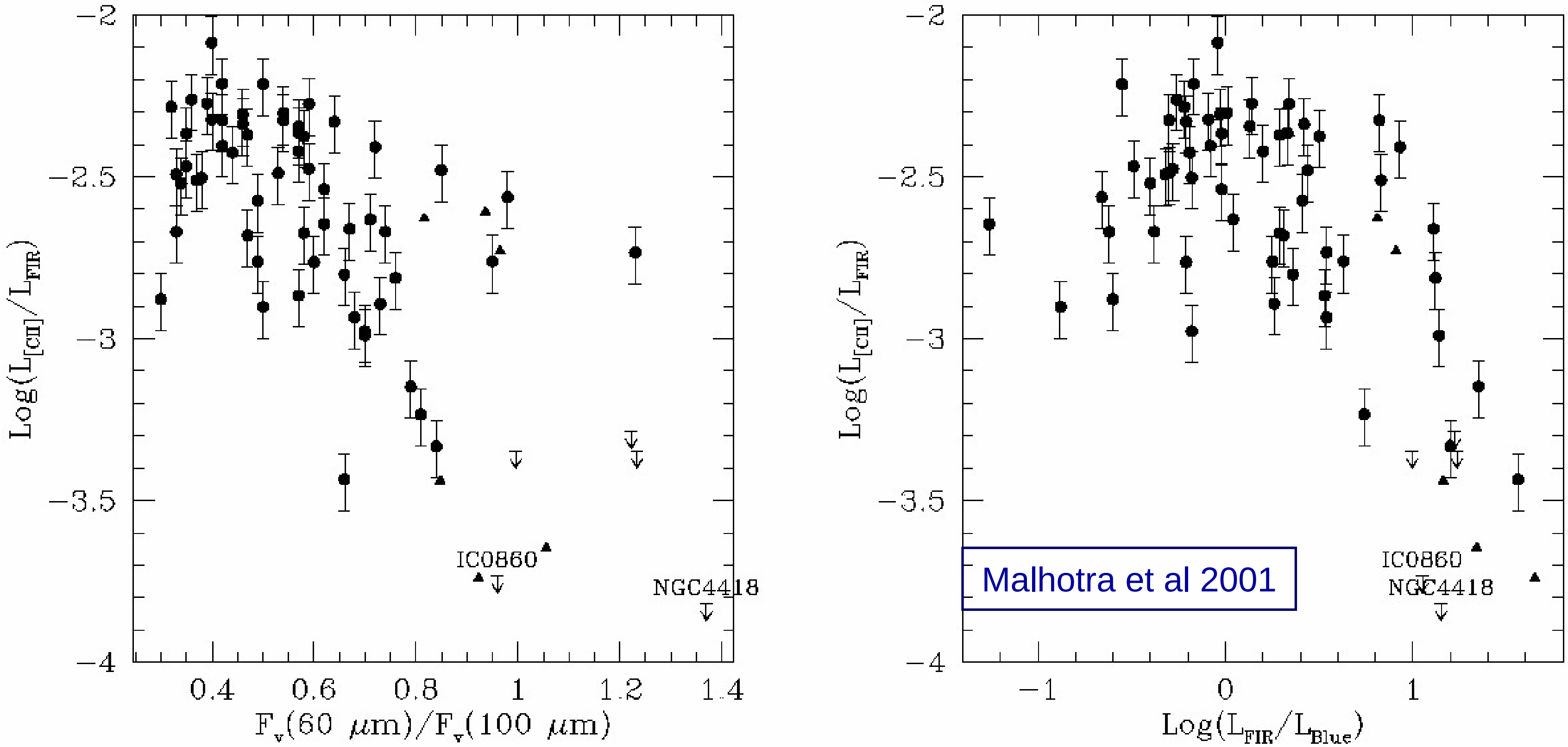


Malhotra et al 2001

Fig. 11.— This figure shows the G_0 and n solution for galaxies based on comparison of data and PDR models shown in figure 11. The filled circles are G_0 and n values estimated from $L_{[OI]}/L_{[CII]_c}$ and $(L_{[OI]} + L_{[CII]_c})/L_{TIR}$; and the open squares are the G_0 and n values derived from $L_{[OI]}/L_{TIR}$ and $F_\nu(60\ \mu m)/F_\nu(100\ \mu m)$. The G_0 and n values derived from the two methods are connected for each source to give an estimate of the uncertainty in the parameters. A least squares fit is made to both sets of G_0 and n values assuming equal error in both axes. The best fit slopes are 1.4 and 1.3 respectively, i.e. $G_0 \propto n^\alpha$, with $\alpha = 1.3-1.4$, which is consistent with the emission coming from PDRs surrounding ionization-bounded expanding H II regions.

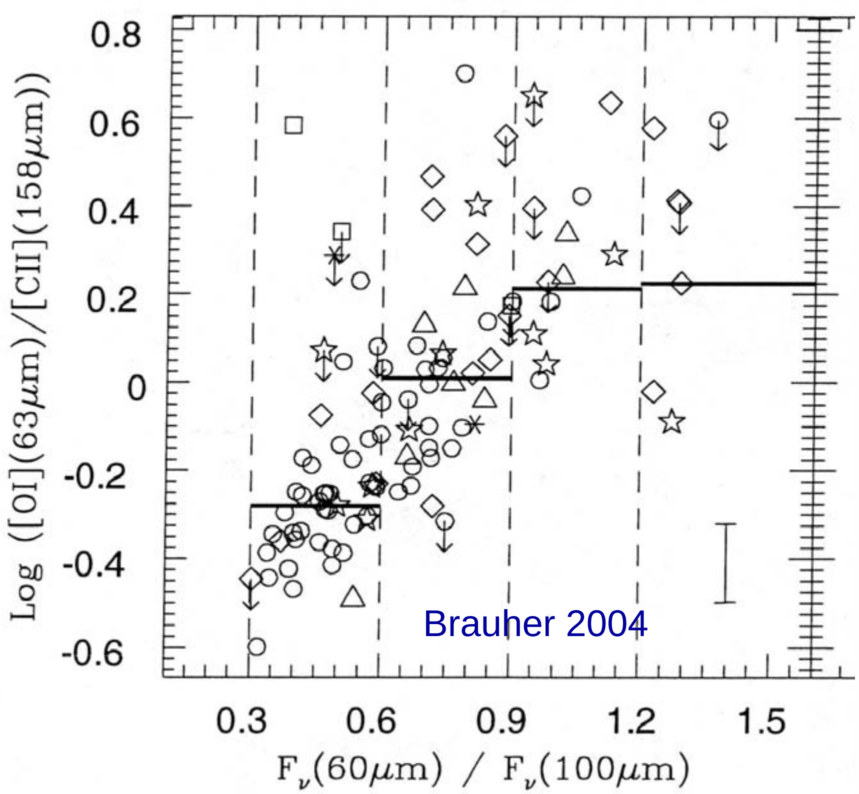
Empirical Approach to FIR Cooling Lines (1)

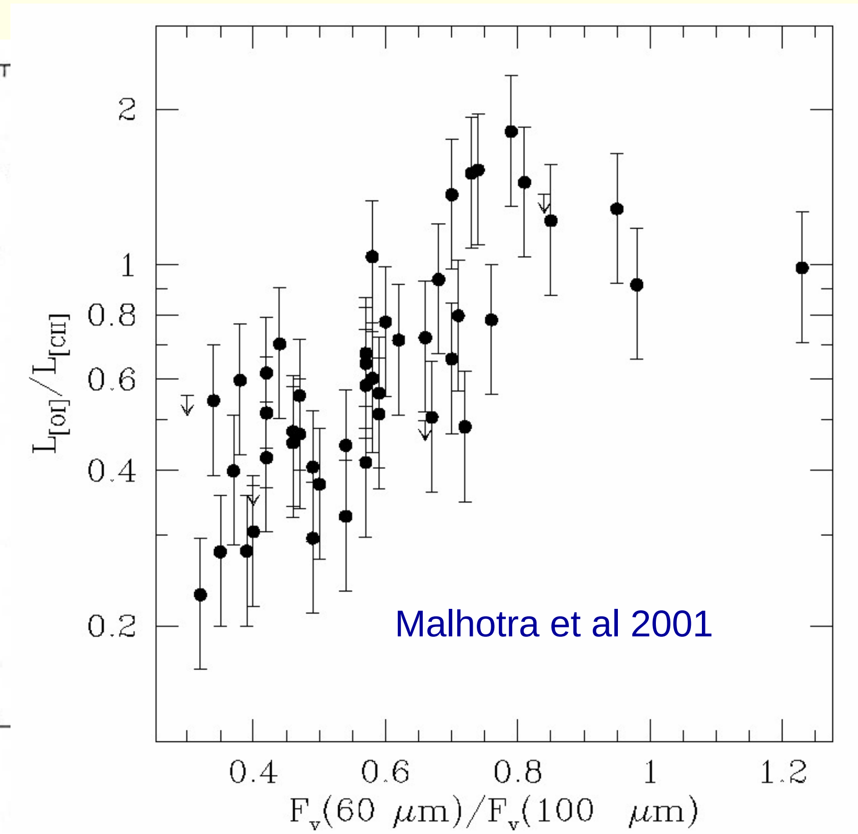
- About 2/3 of galaxies have [CII]/FIR = 0.2 to 0.7%
  - *Max L cooling line, ~10 x H_2(mid-IR), 10^3 x CO→ **promising for high z***
- However, [CII]/FIR decreases by x10-40 with increasing IR/B, f(60)/f(100)
  - *Most likely: higher star formation rate→ more ISM heating→ greater G_0/n*
    - +charged grains; reduced p-e yield; hot dust & cool gas!
  - *Most unlikely: AGN leads to non-PDR conditions*



Empirical Approach to FIR Cooling Lines (2)

- "[CII] deficiency" with increased ISM heating has led to concerns that high-redshift luminous systems will be deficient in [CII]
- However, [CII] is not always the most luminous line
  - *[OI] shows no evidence of "deficiency"*





Implications for High-Redshift Line Surveys

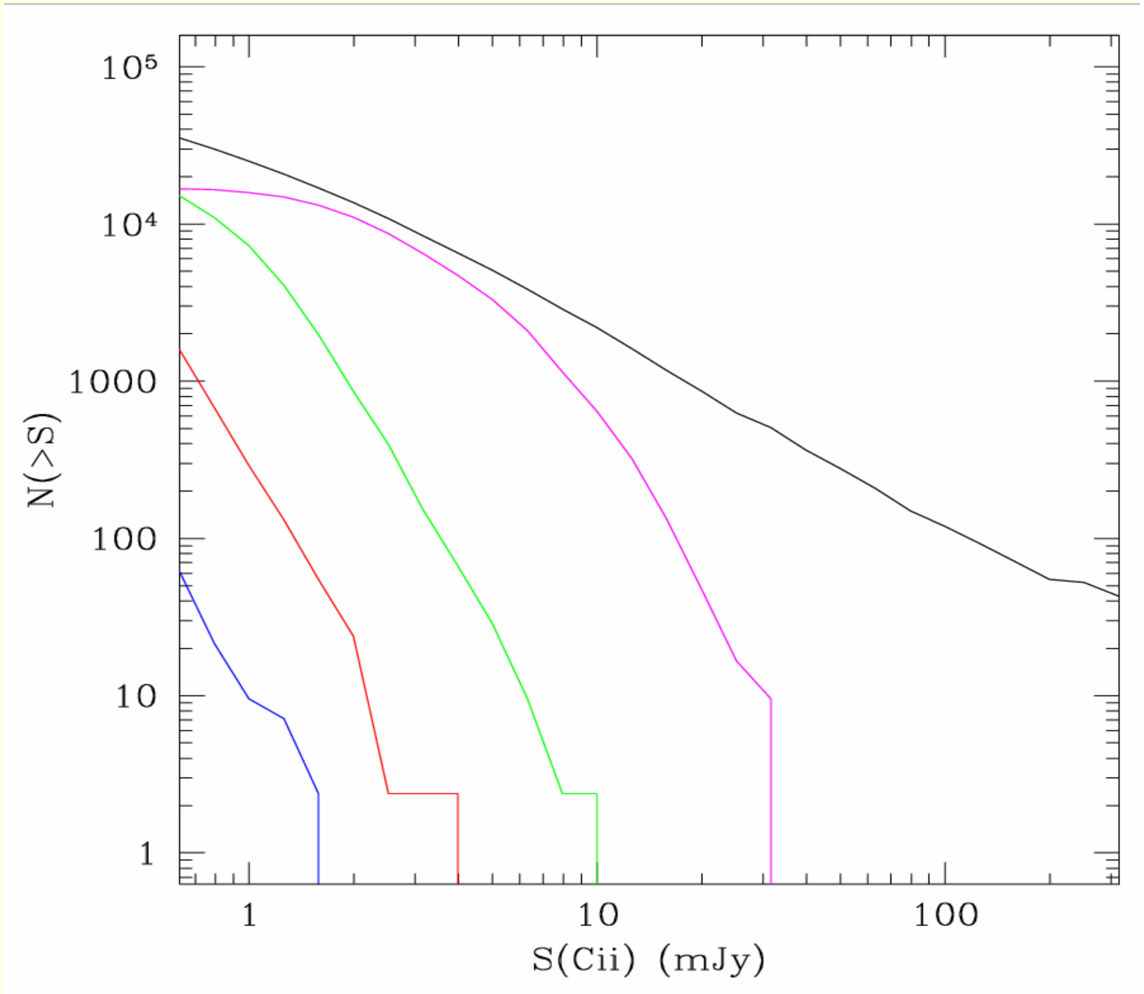
- [CII] will still dominate cooling for FIR-cool high-redshift galaxies
  - *Such objects exist, are luminous, and will be favored in high-z [CII] surveys*
    - E.g. ALMA for z~3 or z~4
- Warm sources, e.g. 60μm ULIRGs, are not good targets for [CII] alone!
- High-z [CII] surveys should be complemented by [OI] and [OIII] surveys
  - *Combination provides a more complete picture of early nucleosynthesis*
  - *This requires 100 μm≤λ≤ 600 μm for the interesting epoch z=1~3*
  - *Concerted line+continuum survey can defeat confusion*

- Detailed line studies of nearby systems can also guide the spectroscopic resolution needed for high-z surveys

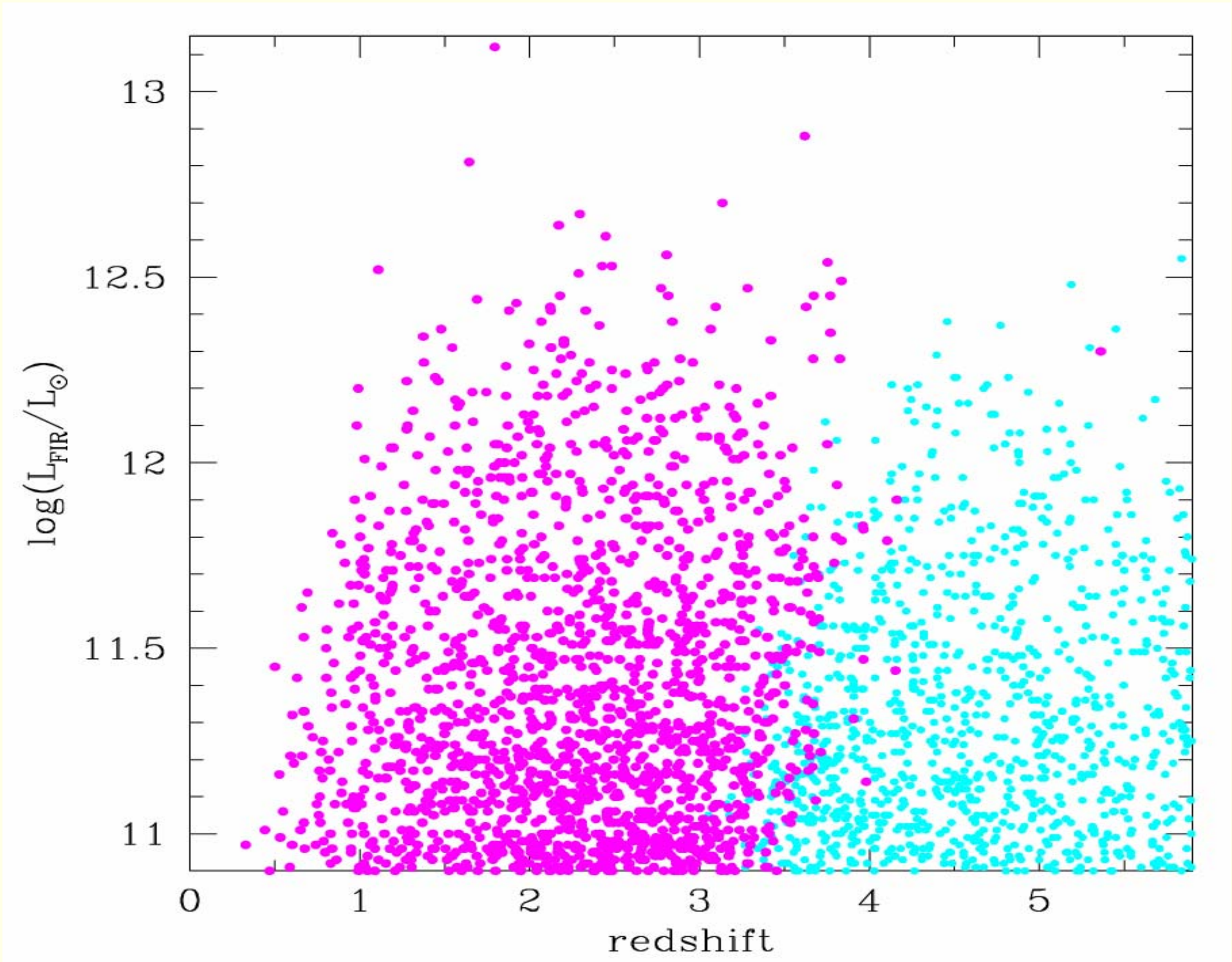
- Simulations of the L-C galaxy population yields predictions to guide high-z line surveys (Helou and Chapman in preparation):
  - *L(AFE) → L([CII]) quite well*
  - *L(FIR) → L([OI]) with more scatter*

CII Surveys

- Predicted number counts of galaxies detected in CII
  - *Contributions of redshift shells at z=1, 2, 3, 4*



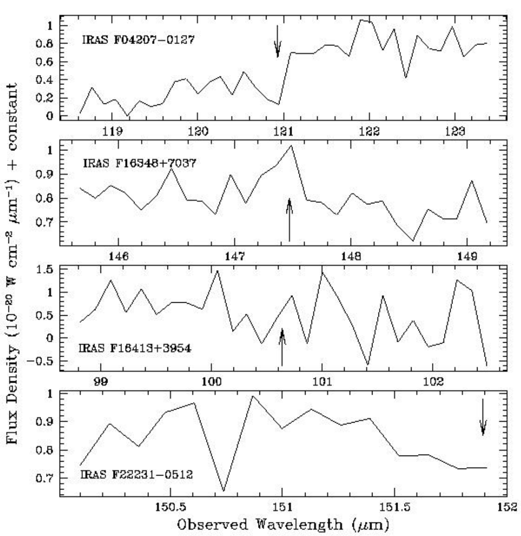
CII Detectability (see Chapman talk)



Study Case: Search for OI 63μm at High Redshift

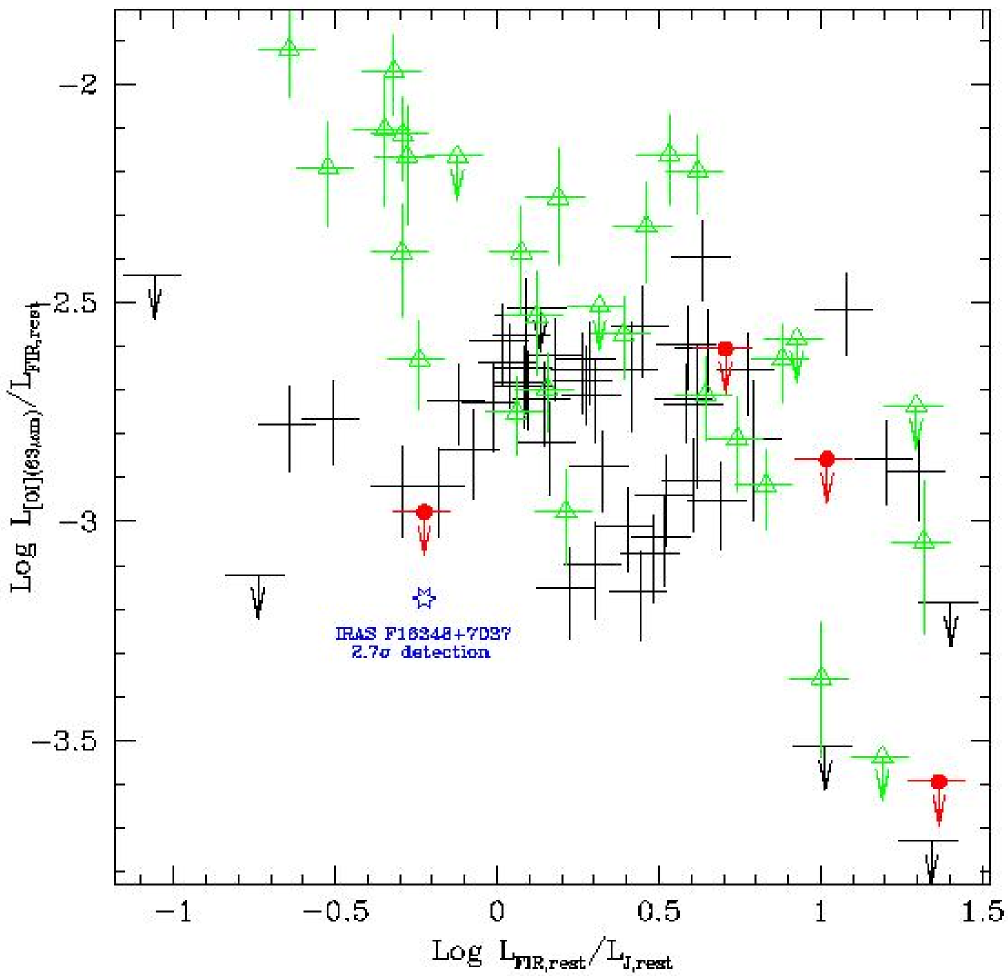
- Four IR Ultra-Luminous galaxies, L(IR)~10^{13} L(sun)
  - *All are "QSO" or "BL Lac", but they have IR/B ratios 1—10, ULIRGs*
- Four to six hours of integration time per source, with ISO-LWS, wavelength tuned to redshifted 63.183705 μm
- No detections, but interesting upper limits, comparable to nearby galaxies
  - *Data do not rule out warm molecular gas in these systems*
  - *Unusual source SED shifts upper limits to less significance*

Source	redshift	log L(FIR) L(sun)	R(60,100) IRAS, Jy	F(OI) 3σ 10^{-17} Wm^{-2}
IRAS F04207-0127	0.915	13.4	~1.67	<3.5
IRAS F16348+7037	1.334	13.6	>1.75	<1.9
IRAS F16413+3954	0.593	13.2	~1.67	<10.
IRAS F22231-0512	1.404	14.4	>1.75	<2.5



Comparison to Normal & Seyfert Galaxies (1)

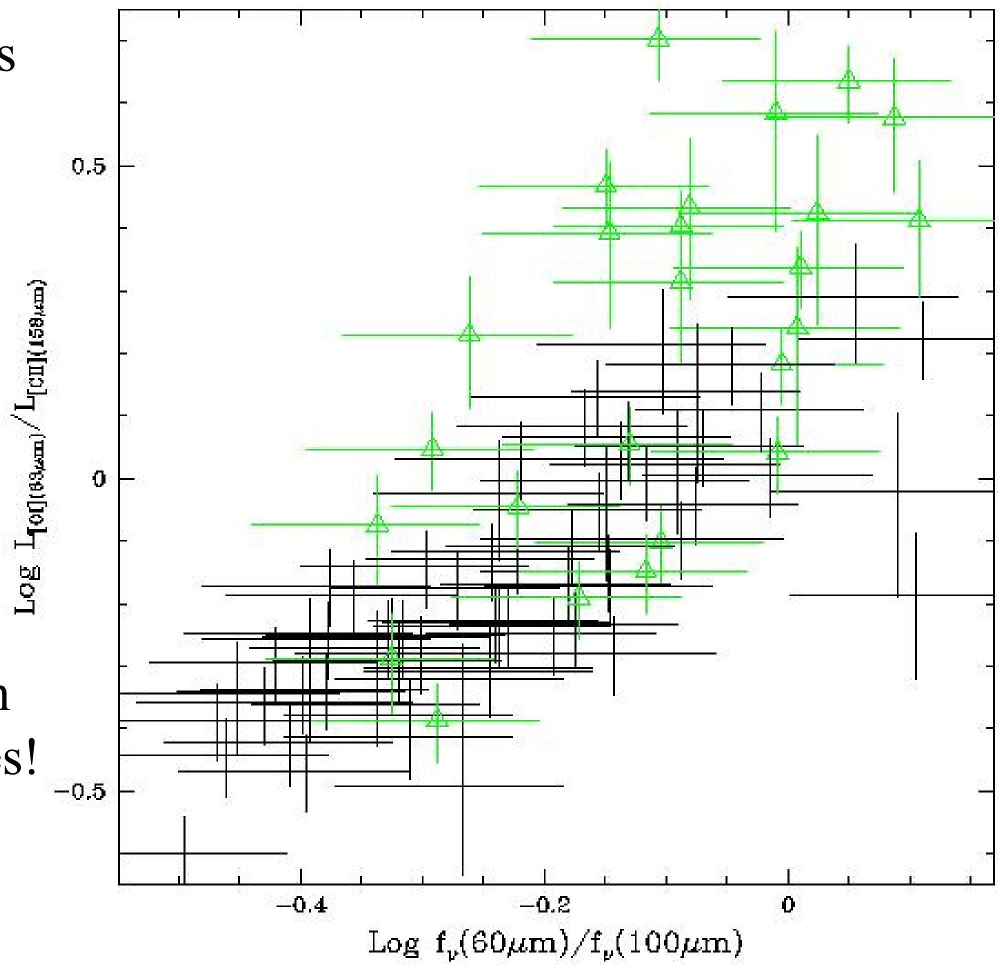
- "Normal" from ISO KP (z<0.1), and Seyfert from Brauher et al compendium and NED typing (z<0.3)
- Goal was to bound the star formation fraction of luminosity
- <u>Surprise</u>: OI is stronger in Seyfert than in Normal galaxies
- <u>No surprise</u>: Maloney et al (1996) had modeled such XDR behavior: X-Ray heating of dense clouds $n>10^5$ would lead to OI > CII emission



Comparison to Normal & Seyfert Galaxies (2)

- As predicted, OI/CII increases even steeper with heating intensity in Seyfert galaxies (XDR) as compared to star powered galaxies (PDR)

- We're only beginning to learn about these fine-structure lines!



Case Study: The Cooling of Arp220

- Malhotra et al (2001) looked in detail at the cooling of the neutral medium in Arp 220, to check whether other transitions make up for CII deficiency
  - *The answer is that all potential cooling channels are depressed*
- Question: Is this a general trend across far-IR lines?
  - *Use Brauher (2004) data set to address*

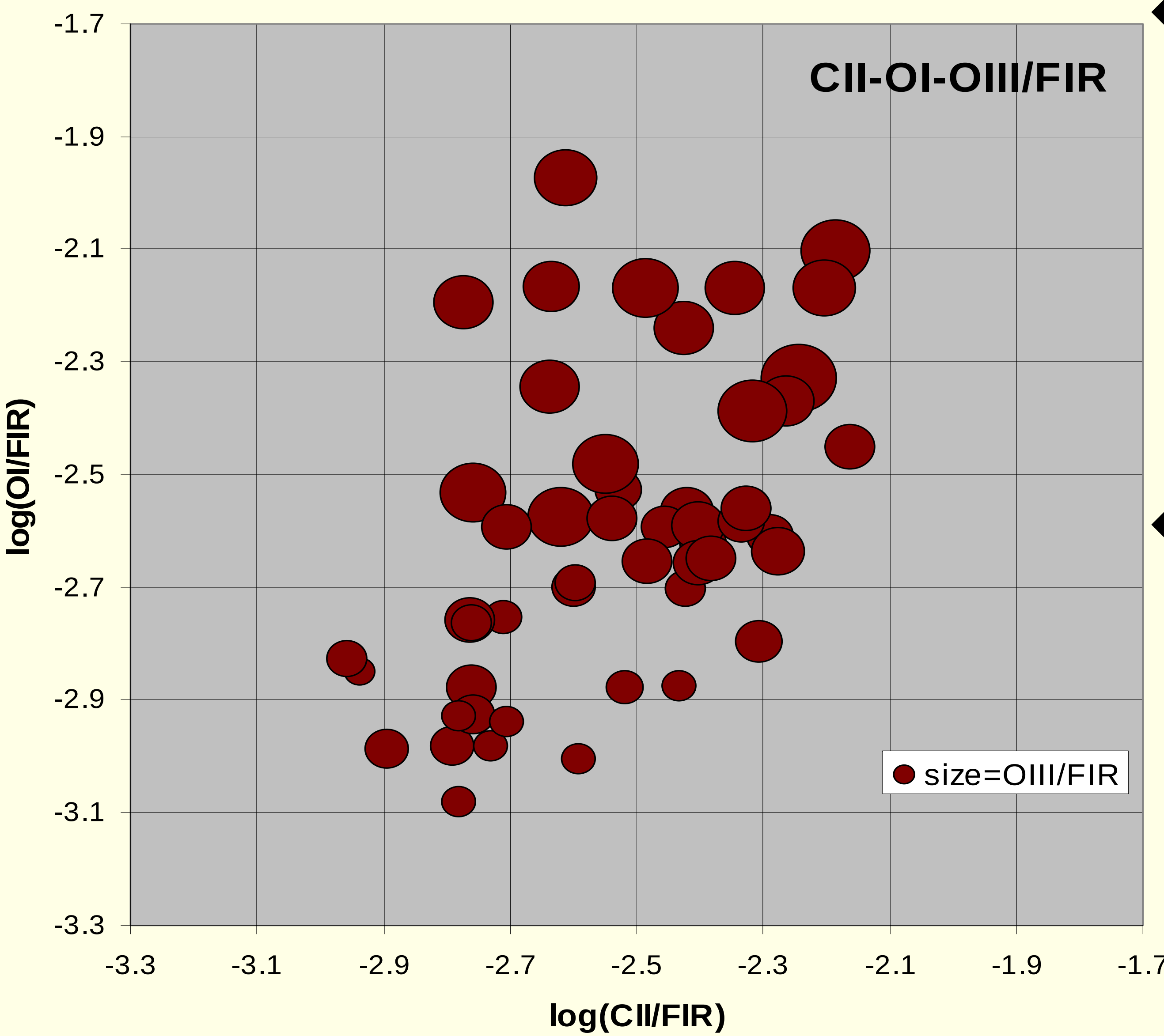
Table 4: Arp 220: Energy Budget

	Flux (observed) (W/m^{-2})	Flux(extinction corrected) (W/m^{-2})
FIR Continuum [1]	6.8×10^{-12}	
[C II] [1]	8.7×10^{-16}	
CI ($^3P_1$-$^3P_0$) [1]	1.9×10^{-17}	
CI (total) [1]	1.0×10^{-16}	
CO (1-0) [1]	1.8×10^{-18}	
CO (total) [1]	2.1×10^{-16}	
H_2 S(5) [2]	2.4×10^{-16}	2.4×10^{-15}
H_2 S(2) [2]	$< 1.5 \times 10^{-16}$	$< 7.0 \times 10^{-16}$
H_2 S(1) [2]	2.3×10^{-16}	9.7×10^{-16}
H_2 S(0) [2]	$< 3.5 \times 10^{-16}$	$< 7.3 \times 10^{-16}$

[1] Gerin & Phillips 1998

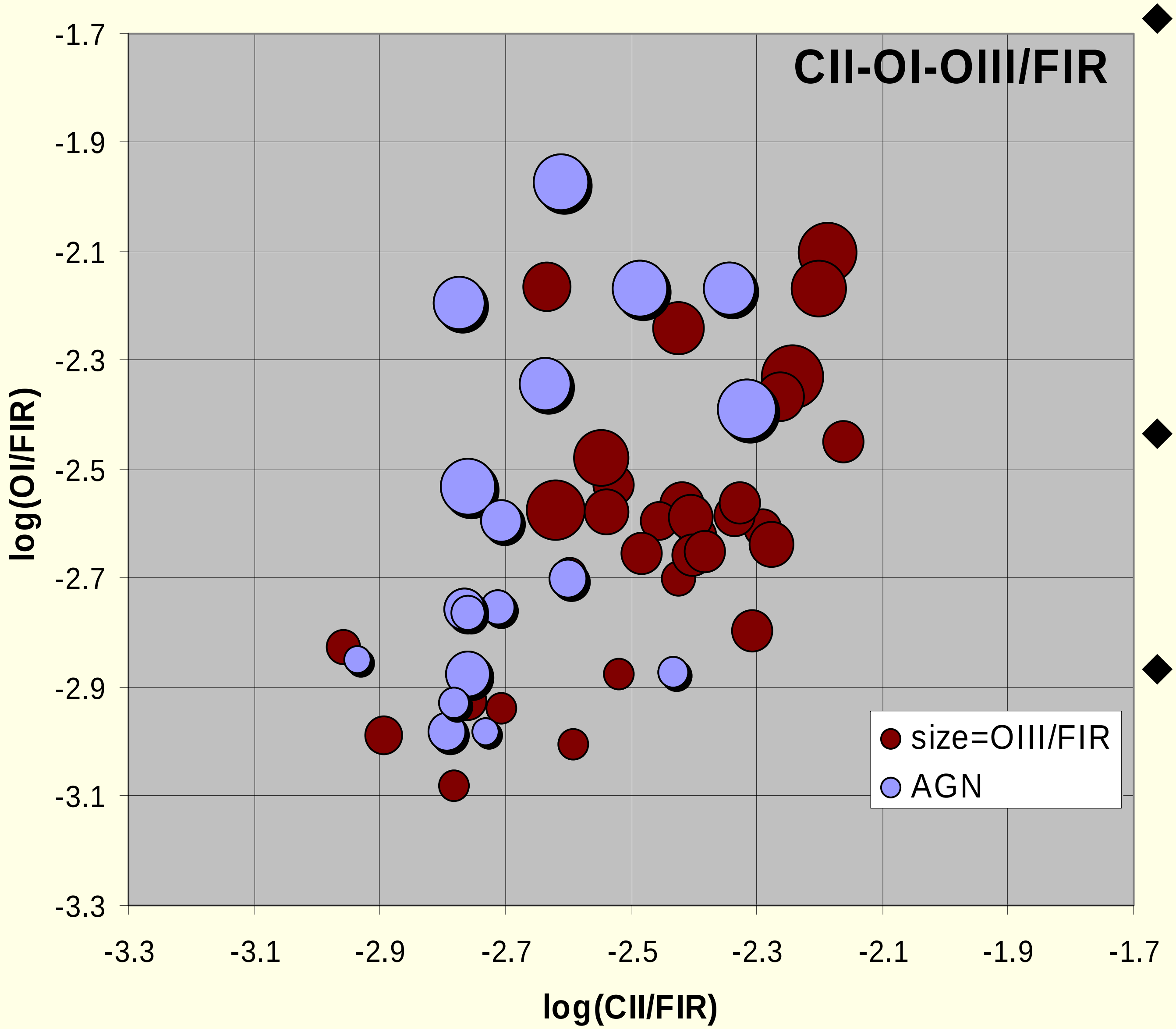
[2] Sturm et al. 1996

Brauher (2004) Data set of ISO-LWS Line Data on Galaxies



- Distills dozens of observations from many observing programs
  - *Provides unique look at global cooling from ISM in galaxies*
- Some galaxies are depressed in all cooling channels
  - *Need more investigation!*

Effects of AGN?

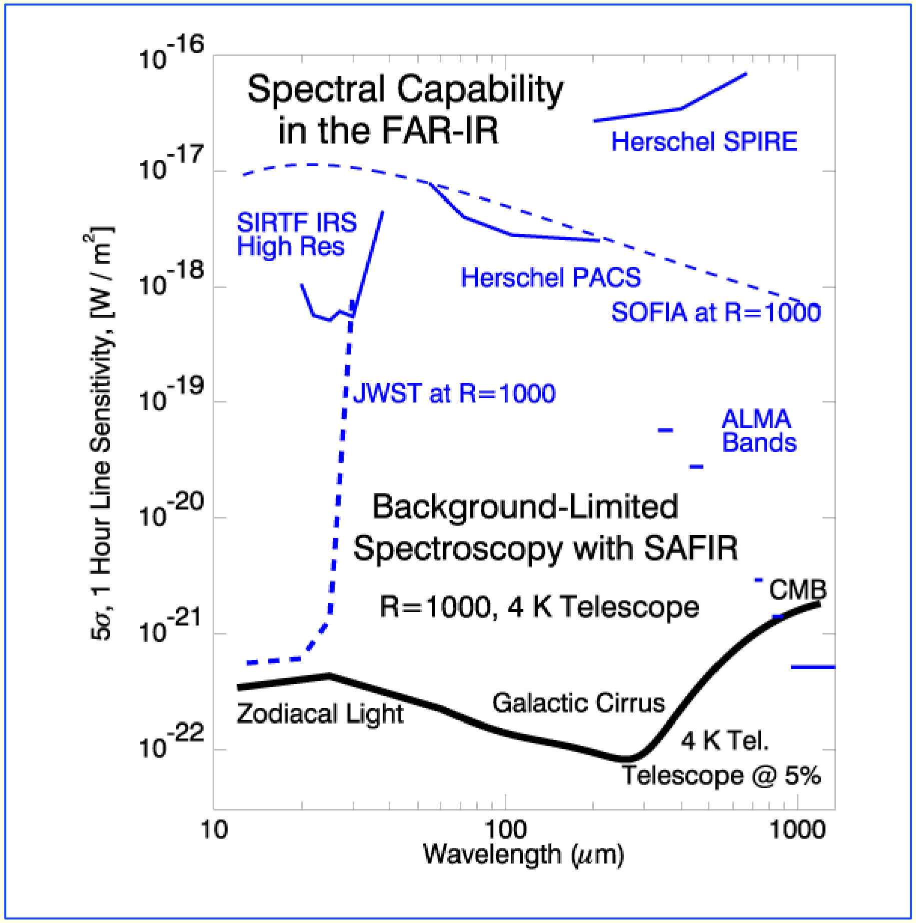


- Much dispersion, sample needs to be "cleaned up", and AGN contribution to FIR in each object quantified
- AGNs appear to favor lower CII/FIR values, and higher OIII/FIR values
- At similar CII/FIR, AGN favor higher values of OI/FIR

Future Prospects

- Spitzer will complete the picture with mid-IR Fine-Structure lines & H_2 lines
  - *Most important are Si II, Fe II, H_2*
  - *Si II in N7331 carries 0.7-1% FIR*
- Herschel (SOFIA) will provide high-resolution maps of nearby galaxies in the FIR Fine-Structure lines
  - *Correlations local (physics-based) or global (scaling relations)?*
- Herschel and SOFIA will detect lines at 0.5% of 10^{12} L(sun) galaxies at z~1, requiring ~3 10^{-18} W/m^2
- All of that will connect ISM diagnostics, relate them to metallicity, age, etc
- SAFIR will be able to pick up lines at 0.5% of L* galaxies out to z~2.5, requiring ~3 10^{-22} W/m^2

Species	λ (μm)	E.P. (eV)	I.P. (eV)	$\Delta E/k$ (K)
[C II]	157.7	11.3	24.4	91
[O I]	63.2		13.6	228
[Fe II]	35.3	7.9	16.2	407
[Si II]	34.8	8.2	16.4	413
H_2 S(0)	28.2			510
[Fe II]	26.0	7.9	16.2	554



Some Parting Thoughts

- Spitzer is demonstrating the power of large FOV instruments to address the big picture via efficient surveys
  - *Important for future missions to be fast and efficient*

- Spitzer studies of extragalactic H_2 lines have yet to yield the first round of results, and will be a major theme for future missions
  - *Especially in combination with Fine-Structure Lines*
  - *Especially in early-galaxy analogs or nascent starburst analogs*

- Theory will remain very important for Aromatics and Fine-Structure Lines
  - *PDR modeling has had major successes (PDR, HII and now combining the two), but needs a quantum jump into modeling realistic geometries rather than layering*